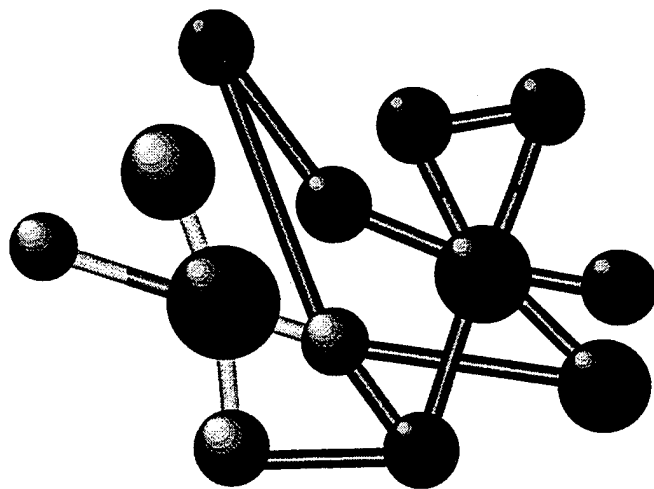




Advanced Materials Technology and Industrial Base

An Analysis and Assessment of Specialty Metals and Advanced Composites



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Preface

This assessment was conducted to examine the extent to which the technology and industrial base for advanced materials can provide assured, affordable access to the leading edge technology products necessary to meet military requirements. The study also explored possible policy options when issues of access were identified.

The Office of the Under Secretary of Defense (Acquisition and Technology) conducted this study with assistance from the military services, the Department of Commerce, the Department of Energy, the Department of the Interior, and the National Aeronautics and Space Administration. Furthermore, both U.S. industry and academia were consulted and provided valuable contributions to the study effort.

This study was directed by Dr. Richard Van Atta, Special Assistant for Dual Use Technology Policy. Jerome Persh (Office of the Director, Defense Research and Engineering) was the team leader for this effort. DoD participants contributing to the study report include: Dan Dennison, Andy Gilmour, Cynthia Gonsalves, Mary Grafton, Jay Mandelbaum, Linda Mareth, Dan McMahon, Dan McMorrow, Mike Soboroff, and Frank Traceski (all of the Office of the Assistant Secretary of Defense, Economic Security); Bob Crowe (Advanced Research Projects Agency); Bob Katz (Army); Al Bertram and Jim Kelly (Navy); and Larry Hjelm (Air Force).

The Institute for Defense Analyses (IDA) provided technical support to the study team. The assistance of Jim Bell, Charles Bersch, Bill Hong, Mike Rigdon, Janet Sater, and George Sorkin in producing this report is greatly appreciated. IDA also convened an industry review group to support this assessment as follows: Dr. Alan G. Chynoweth (Bellcore, retired), Dr. Julius Harwood (Ford Motor Corporation, retired), Dr. S. Norm Kakarala (General Motors), Mr. William Manley (Cabot Corporation, retired), Dr. Robert J. Russell (Norton Company, retired), and Dr. Albert R.C. Westwood (Sandia National Laboratories).

The cooperation of the DoD Defense Technical Information Center's Information Analysis Center Project Office is gratefully acknowledged for authorizing the Purdue Ceramics Information Analysis Center to conduct a series of four workshops in support of this assessment. These workshops were attended by about 140 representatives (roughly 50 percent industry, 40 percent government, and 10 percent academia).

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Executive Summary

This study was initiated to assess the ability of the advanced materials technology and industrial base to meet military requirements to (1) maintain technological superiority in a fiscally austere and changing national security environment and (2) improve the affordability and the use of technological innovation.

The Joint Staff and the Joint Requirements Oversight Council have identified five Future Joint Warfighting Capabilities that are most needed by U.S. Combatant Commands when U.S. forces use or threaten to use military power in protecting vital and important U.S. national interests as follows:

- (1) Maintain and communicate near perfect real time knowledge of the enemy.
- (2) Engage regional forces promptly in decisive combat on a global basis.
- (3) Employ a range of capabilities which allow achievement of military objectives with minimum casualties and collateral damage.
- (4) Control the use of space.
- (5) Counter the threat to the continental U.S. and deployed forces created by weapons of mass destruction and missiles.

Our defense programs to achieve these capabilities must be structured to maintain these warfighting capabilities into the future while cutting costs and ensuring that we get the most from every defense dollar. Consequently, military needs for advanced materials should be based not only on their essentiality in meeting the Joint Staff Warfighting Capabilities but also on achieving increased affordability, performance and longevity for DoD hardware that supports these capabilities.

This study was conducted within the context of the Defense Department's Dual Use Technology Strategy. This Strategy points out the criticality of defense programs taking advantage of cost-conscious, market-driven commercial production and leveraging the huge investments in leading edge process technologies made by private industry. It also shows the importance of defense technologies and systems keeping pace with the rapid product development cycles driven in critical areas by a highly dynamic commercial sector.

Therefore, this study specifically assesses the extent to which the commercial capabilities of the technology and industrial base for advanced materials can provide access to the leading edge technology products necessary to meet military requirements. When access is assured, the study also examines whether commercial capabilities will be sufficient by themselves or if there are issues concerning affordability or the availability of the high end technology.

Not all advanced materials are assessed in this report. The term "advanced materials" can have as many different meanings as there are materials in the industry. This study is focused on load carrying structural materials that provide current or future technology advantage when

applied to military structures. Consequently, this assessment divides advanced materials into two sectors which encompass two primary classes of structural materials:

- (1) **Specialty Metals** Specialty metals encompass metals and metal alloys that have outstanding high temperature strength and oxidation resistance or enable extremely weight efficient structures at more moderate temperatures. Superalloys, titanium, and beryllium are assessed in this report.
- (2) **Advanced Composites** Advanced composites are homogeneous matrix materials reinforced with either continuous fibers or particulates that are engineered to provide specific properties that facilitate extraordinary design capabilities. Polymer matrix composites (PMCs), ceramic matrix composites (CMCs), metal matrix composites (MMCs), and high thermal conductivity composites are assessed in this report.

Specialty metals are commonly found today in many military applications such as combat airframes, turbine engines, optical subsystems, armored vehicles, and nuclear weapons. Superalloy and titanium products are critical to military gas turbine engines used in fixed and rotary wing aircraft, cruise missiles, armored vehicles, and water craft propulsion as well as auxiliary power generators for aircraft, ship and ground stations. Titanium is also vital to airframes, where it is used in critical, highly loaded and high temperature components and for the compatibility required for the metal parts of composite airframes. The high specific strength of titanium alloys, coupled with excellent corrosion resistance and relatively good low temperature capability make titanium an important material for cryogenic pressure vessels for liquid fueled missiles, tanks and structural components of space vehicles designed to operate in cryogenic temperatures, and various sea water systems. It is also used for ordnance components and armor. Beryllium is critical to many specialized military applications where its combination of low density, high stiffness to weight ratio, and thermal conductivity are unsurpassed. The use of beryllium in precision optics and thermal management applications is particularly important to the performance of a wide range of airborne and space reconnaissance, and air, sea and land weapon systems. Its dimensional stability over a wide temperature range is important to military inertial navigation systems. As a neutron reflector, beryllium is also used in both nuclear reactors and nuclear weapons.

Advanced composites represent emerging, enabling technologies that portend growing military applications in the future due to their strength, wear resistance, low density, and dimensional stability. Advanced polymer matrix composites are used mostly in military aerospace applications requiring outstanding strength and stiffness at minimum weight. The use of these materials to extend the operating life, decrease fuel consumption, and reduce maintenance requirements for systems currently in the field is now beginning to occur. Military aircraft jet engines utilizing ceramic matrix composites components will be lighter and more capable of operating at higher temperatures without cooling, resulting in increased propulsion efficiency, greater payload carrying ability, greater range, and higher performance. Ceramic matrix composites will reduce the infrared signature of military aircraft engines and engine related structures, thus enhancing survivability. Metal matrix composites are expected to be used

in a wide variety of military applications including aircraft, missiles, space structures, ground vehicles, and propulsion systems to reduce weight, size, fuel usage, and life cycle costs; thereby increasing range, payload, velocity, and stand-off distance and consequently improving survivability and maintainability. High thermal conductivity composites are focused on spacecraft requirements for high stiffness, low mass, and dimensional stability. Additionally, they are vital to increasing the reliability of sensitive electronic and spacecraft systems.

The identification of potential concerns of assured, affordable access and the determination of possible policy options to deal with them in the advanced materials sector are complicated by: (1) new approaches to defense acquisition; (2) issues concerning the transition of one advanced material to another; and (3) the number of tradeoffs to be considered in funding the transition to a new material. As described in the Dual Use Strategy, possible options include: (1) investment in research and development on dual use technologies to ensure our commercial technology base remains at the leading edge in areas critical to the U.S. military; (2) integration of military technologies into commercial production (through transition into commercial applications or developing and deploying new manufacturing technologies for more affordable capabilities); and (3) insertion of commercial capabilities into military systems. The following paragraphs summarize the findings of this assessment.

The analyses of specialty metals are more straightforward than those for advanced composites. Specialty metals have been used for a long time and DoD as well as commercial applications are widespread. Corresponding to declining defense requirements, the industry is facing significant reductions in defense spending which is a large portion of the industry's business base. There could be additional market pressures from low price competition from the former Soviet Union (beryllium). These dual pressures are causing some industry restructuring. However, to varying extents, increased commercial applications offset some of the military sales declines (to a large extent for beryllium products except metallic beryllium, some impact for titanium, and little impact for superalloys). The long term (10 to 20 years) defense market outlook is weak because of the rising competition with advanced composites (assuming composite costs decrease significantly).

Concerning issues of assured, affordable access to superalloys, titanium, and beryllium to satisfy defense needs, this study has, as of now, concluded that: (1) the industrial bases for these specialty metals will downsize to reduce overcapacity according to normal competitive market forces; (2) this downsizing will not be inconsistent with future defense requirements; and (3) therefore issues of assured or affordable access do not appear significant. In the case of titanium, this study also found that new military demand could emerge if prices were reduced by 40 percent or more. However, it is the responsibility of industry to address these cost reduction issues unless a specific cost benefit analysis shows that it is in the best interest of DoD to take action.

PMCs are the most mature of the advanced composites examined in this assessment. In this regard, the situation is similar to specialty metals. There are numerous DoD and commercial applications and the industrial base is mature. The industrial base is restructuring because of declines in defense spending (principally PMC fabricators), however the changes are not severe.

Increased commercial applications in some cases have already, and in other cases will soon, offset the military sales declines. In fact, DoD demand is expected to grow, but not as rapidly as commercial demand.

Concerning issues of assured, affordable access to PMCs to satisfy defense needs, based on data examined to date, this study has concluded: (1) there is little doubt that the PMC industrial base will be able to satisfy military needs in the future; (2) there are certain areas (pitch-based carbon fibers, PMC fabrication) where the costs to DoD could be reduced, and projects are underway to attempt to achieve such cost reductions; and (3) if potential insertion opportunities arise, they may improve DoD's access to PMCs, however DoD funding for any such project must be contingent on that project passing a cost-benefit test on its own merits.

CMC technology is less mature than PMC technology. The industrial base is healthy and growing rapidly for discontinuous CMCs (dCMCs); the industrial base is small but beginning to exhibit stability and growth potential for continuous CMCs (cCMCs). Structural dCMCs have been used by DoD and the commercial world for many years (primarily as cutting tools), and there is a very large industrial base available for other ceramics applications. cCMCs are an emerging technology. In fact, government spending has not declined significantly, only its growth has been slower than anticipated a few years ago.

Concerning issues of assured, affordable access to CMCs to satisfy defense needs, this study has, at this time, concluded: (1) there is little doubt that the CMC industrial base will be able to satisfy military needs in the future; (2) Department of Energy investments in CMCs will serve DoD needs in that those capabilities being developed will also satisfy military requirements, therefore it is not necessary for DoD to have the lead in technology development; (3) as was the case with PMCs, if potential CMC insertion opportunities arise, DoD funding support should be contingent on a demonstration that the expected life cycle costs to DoD are reduced as a result of the project and that the inserted product performs at least as well as the item it replaced.

Applications of MMC technology are less mature than CMC technology. The market for discontinuous MMCs (dMMCs) is small and not stable even though there is substantial installed capacity; the industrial base for continuous MMCs (cMMCs) is precompetitive. Both dMMCs and cMMCs are emerging technologies. The principal difference, in contrast to CMCs, is that potential DoD demand for MMCs is far greater and DoD has a clear interest and leadership role in seeing this technology move into application for improving both the performance and affordability of weapon systems. Potential dMMC DoD demand may be the highest of the advanced composites examined.

Concerning issues of assured, affordable access to MMCs to satisfy defense needs, this study has concluded: (1) there are potential issues of assured, affordable access -- industry is not capable of satisfying a high volume DoD demand for cMMCs; (2) low volume production costs are high; (3) while the use of cMMCs provide several near term opportunities to reduce total DoD life cycle costs and to improve the military capability of gas turbine engines, the current precompetitive industrial base cannot produce the cMMCs in sufficient volume; (4) the

numerous technical and economic barriers to widespread use identified in this assessment cannot be overcome by industry alone -- there has been little application specific investment to ensure an item can be produced; (5) the identified technical and economic problems are not insurmountable -- a project was identified to establish long term, viable cMMC producers capable of meeting potential DoD quantity demands by transitioning manufacturing technology developed by industry from pilot scale to full scale production; and (6) DoD has not quantified high volume requirements for dMMCs -- while access seems assured, the issue of affordability cannot be addressed until the demand is well established.

High thermal conductivity composites are the least mature of the advanced materials examined in this report. The industrial base is precompetitive. DoD demand is small and for very expensive, high end technology. DoD demand for specifically designed, limited production components can be met with the current industrial base structure.

Concerning issues of assured, affordable access to high thermal conductivity composites, this study has concluded that currently: (1) there are no issues of assured access, and DoD is funding its unique requirements; (2) DoD costs will probably not decline substantially because of low volume production; (3) lower DoD costs and increased DoD usage will only occur when volume commercial production applications materialize, and based on current needs and costs, it would be incumbent on industry, not DoD, to develop such commercial applications and markets; and (4) should an insertion project materialize, funding support must be justified by a cost-benefit analysis.

Overall, this assessment has found that, with certain exceptions, assuming the programs ongoing in DoD and other government agencies continue as planned, the technology and industrial base for advanced materials is currently adequate for meeting future military requirements.

CHAPTER 1: INTRODUCTION

This study was initiated to examine the extent to which the technology and industrial base for advanced materials can provide assured, affordable access to the leading edge technology products necessary to meet military requirements. When issues of access were identified, the study explored possible policy options to address the situation. The report is organized as follows: Chapter 1 is the introduction and overview; Chapter 2 is the specialty metals assessment, focusing on three specialty metals: superalloys, titanium, and beryllium; Chapter 3 is the advanced composites assessment, focusing on four advanced composites: polymer matrix composites, ceramic matrix composites, metal matrix composites, and high conductivity graphite fiber composite thermal management materials; Chapter 4 summarizes the conclusions from Chapters 2 and 3.

1.1 Assessment Objective

The Joint Staff and the Joint Requirements Oversight Council have identified five Future Joint Warfighting Capabilities (see Table 1.1) that are most needed by U.S. Combatant Commands¹ when U.S. forces use or threaten to use military power in protecting vital and important U.S. national interests.

Table 1.1 - List of Five Future Warfighting Capabilities Defined by the Joint Chiefs of Staff

- | | |
|------|--|
| I. | Maintain and communicate near perfect real time knowledge of the enemy. |
| II. | Engage regional forces promptly in decisive combat on a global basis. |
| III. | Employ a range of capabilities ... which allow achievement of military objectives with minimum casualties and collateral damage. |
| IV. | Control the use of space. |
| V. | Counter the threat to the continental U.S. and deployed forces created by weapons of mass destruction and missiles. |

Our defense programs to achieve these capabilities must be structured to “maintain[s] these warfighting capabilities into the future while cutting costs and ensuring that we get the

¹ *Defense Science and Technology Strategy*, Department of Defense, Director, Defense Research and Engineering, September 1994, p. 3.

most from every defense dollar.”² Consequently, military needs for advanced materials should be based not only on their essentiality in meeting the Joint Staff Warfighting Capabilities, but also on achieving increased affordability³, performance and longevity for DoD hardware that supports these capabilities.

This study was initiated to assess the ability of the advanced materials technology and industrial base⁴ to meet military requirements to (1) maintain technological superiority in a fiscally austere and changing national security environment; and (2) improve the affordability and the use of technological innovation. The performance and durability of military hardware represent a balance between military requirements and the ability and cost to fabricate systems with the desired characteristics. In the design process, advanced materials enable the balance to be tilted in favor of increased performance, improved durability, decreased life cycle costs, etc. by providing capabilities not achievable with other materials of construction. However, there are three necessary conditions that allow such balancing to be made: (1) improved performance of the material over time, (2) the ability to fabricate the necessary components, and (3) early, assured and affordable access to the material. The DoD Science and Technology (S&T) Program addresses these first two issues through the Materials, Processes, and Structures Technology and the Manufacturing S&T Area Plans.⁵ The third issue is the subject of this assessment.

This study was conducted within the context of the Defense Department’s Dual Use Technology Strategy.⁶ This Strategy was developed in recognition of the fundamental challenge facing defense acquisition today:

*Rapid advances in commercial technology combined with declining U.S. defense budgets have, in many cases, rendered DoD’s traditional, defense-unique approach to technology development and procurement requirements less affordable and less effective than in the past. It is critical that defense programs take advantage of cost-conscious, market-driven commercial production and leverage the huge investments in leading edge process technologies made by private industry. It is also important that defense technologies and systems keep pace with the rapid product development cycles driven in critical areas by a highly dynamic commercial sector.*⁷

Therefore, this study specifically assesses the extent to which the commercial capabilities of the technology and industrial base for advanced materials can provide access to the leading edge technology products necessary to meet military requirements. When access is assured, the

² Annual Report to the President and Congress, William J. Perry, Secretary of Defense, February 1995, p. iii.

³ Measured by total life-cycle costs.

⁴ The term “technology and industrial base” is used in this report to include both companies that develop technology and companies that manufacture products using that technology. No assumption is made concerning whether the same company is involved in both. When the term “industrial base” is used by itself, the focus is on manufacturing activities.

⁵ The Department of Defense Science and Technology Detailed Technology Area Plan (DTAP) on Materials, Processes, and Structures, Draft, 20 June 1994.

⁶ Dual Use Technology: A Defense Strategy for Affordable, Leading-Edge Technology, February 1995.

⁷ Ibid., p. 1.

study also examines whether commercial capabilities will be sufficient by themselves or if there are issues concerning affordability or the availability of the high end technology. Table 1.2 illustrates how the results of this study may be used to evaluate possible policy options. As described in the Dual Use Strategy, possible actions include: (1) investment in research and development (R&D) on dual use technologies to ensure our commercial technology base remains at the leading edge in areas critical to the U.S. military; (2) integration of military technologies into commercial production (through transition into commercial applications or developing and deploying new manufacturing technologies for more affordable capabilities); and (3) insertion of commercial capabilities into military systems.

Table 1.2 - Dual Use Technology Assessments Drive Policy Choices

Possible Actions	Defense Unique Technology Needed for Military Requirements	Commercial Capabilities Can Meet Some Military			
		Access is Assured & Commercial Capabilities Alone Will Be Sufficient	Access is Assured but DoD Needs Affordability in High End Technologies	Access is Assured but DoD Needs to Ensure Commercial suppliers can supply Leading Edge Technology	DoD Needs Assured Access to Technology and Industrial Capabilities
R&D Investment	X			X	X
Develop and Deploy New Manufacturing Technologies	X		X		X
Transition Defense Technology to Commercial Applications			X		X
Insertion of Commercial Technology		X	X	X	X

Section 1.2 provides more information about some of the specific uses of advanced materials in meeting military requirements. Section 1.3 describes some of the concerns regarding the advanced materials technology and industrial base that led to the initiation of this study.

1.2 Application of Advanced Materials to Military Needs

As stated earlier, military requirements for advanced materials are based on their ability to increase affordability, performance, and longevity in DoD hardware crucial to meeting the Joint Chiefs of Staff Warfighting Capabilities. This section provides examples of how advanced materials already in the field are contributing to such requirements and examples of how advanced materials under development are expected to contribute in the future.

Not all advanced materials are assessed in this report. The term "advanced materials" can have as many different meanings as there are materials in the industry. This study is primarily focused on load carrying structural materials that provide current or future technology advantage

when applied to military structures. Consequently, this assessment divides advanced materials into two sectors which encompass two primary classes of structural materials:

- (1) **Specialty Metals** Specialty metals encompass metals and metal alloys that have outstanding high temperature strength and oxidation resistance, or enable weight efficient structures at more moderate temperatures. Superalloys, titanium, and beryllium are assessed in this report.
- (2) **Advanced Composites** Advanced composites are homogeneous matrix materials reinforced with either continuous fibers or particulates that are engineered to provide specific properties that facilitate extraordinary design capabilities. Polymer matrix composites (PMCs), ceramic matrix composites (CMCs), metal matrix composites (MMCs), and high thermal conductivity composites are assessed in this report.

The following discussion lists more specific applications of the specialty metals and advanced composites examined in this report.

Specialty Metals

Specialty metals are commonly found today in many military applications such as combat airframes, turbine engines, optical subsystems and nuclear weapons. Specific DoD uses for each of the three specialty metals examined in this study are illustrated below:

- Superalloy and titanium products are critical to both military gas turbine engines used in fixed and rotary wing aircraft, cruise missiles, the Abrams tank, and some key water craft propulsion and auxiliary power generators for aircraft, ship and ground stations. Future engines will continue to rely on these materials with improvements in titanium and superalloys being especially critical to needed engine performance improvements and component cost reduction. The F-119 engine that will power the F-22 illustrates the use of titanium and polymer matrix composites in the cooler fan section of the engine. As temperatures increase in the compressor section, the use of titanium gives way to higher temperature capable superalloys which are also utilized in the combustor and turbine sections of the engine where the gas temperature rises above the melting point of steel.
- Titanium is also vital to airframes, where it is used in critical, highly loaded and high temperature components and for the compatibility required⁸ for the metal parts of composite airframes. Only two combat airframes designed in the past 25 years have less than 22 percent titanium. More than 50 percent of the weight of the airframe for the F-22 fighter aircraft now being developed by the Air Force is

⁸ Aluminum, for example, may corrode when in contact with carbon fiber-reinforced polymer composites.

made up of advanced composites and titanium. The high specific strength of titanium alloys, coupled with excellent corrosion resistance and relatively good low temperature capability make titanium an important material for cryogenic pressure vessels for liquid fueled missiles, tanks and structural components of space vehicles designed to operate in cryogenic temperatures, and various sea water systems. It is also used for ordnance components and armor.

- Beryllium is critical to many specialized military applications due to its combination of low density, high stiffness to weight ratio, and thermal conductivity. Precision optics and thermal management applications are particularly important to the performance of a wide range of airborne and space reconnaissance, and air, sea and land weapon systems. Its dimensional stability over a wide temperature range is important to military inertial navigation systems. As a neutron reflector, beryllium is also used in both nuclear reactors and nuclear weapons.

Advanced Composites

Polymer matrix composites are often used in today's military propulsion systems because of their specific strength and stiffness. The other advanced composite classes assessed in this study (CMCs, MMCs, and high thermal conductivity composites) represent emerging technologies. Their high temperature capability, strength, wear resistance, low density, and dimensional stability portend growing military applications in the future. Example DoD uses for each of these four types of advanced composites are shown below:

- Advanced polymer matrix composites are used mostly in military aerospace applications requiring outstanding strength and stiffness at minimum weight (savings of 15 to 50 percent when compared with high strength aluminum and titanium). For example, about 20 percent of the structural weight of the F/A-18E/F airframe will be constructed of carbon fiber epoxy composites. The new Titan IV solid rocket motor upgrade, which is also constructed of PMCs, will replace the current steel solid rocket booster to improve performance, reliability and corrosion resistance. Also, parts of the fan for the F-119 engine that will power the F-22 use PMCs. The use of these materials to extend the operating life and reduce maintenance requirements for systems currently in the field is now beginning to occur. An application of PMCs to an existing system is the boron fiber reinforced polymer composite patch that was developed to repair fatigue cracks in the internal wing structure of aging C-141 transports. Another example is the development of a new high temperature polymer matrix composite to replace damaged trailing edges on the F-117A.
- Ceramic matrix composites are an emerging, enabling technology that can enhance the survivability and significantly increase the operating efficiency of

many high temperature military systems. In particular, the use of CMCs to reduce the signature of military aircraft engines and engine related structures is critical to increasing the survivability of expensive aircraft on military missions by making them less vulnerable to infrared detection. Additionally, jet engines utilizing CMC components will be lighter and will be capable of operating at higher temperatures without cooling. These characteristics will pay large dividends in increased propulsion efficiency, leading to greater payload carrying ability, greater range, higher performance, etc.

- Metal matrix composites are expected to be used in a wide variety of military applications including aircraft, missiles, space structures, ground vehicles, and propulsion systems. The benefits of MMC use include reduced weight, size, fuel usage, and life cycle costs; increased range, payload, velocity, and stand-off distance; and improved survivability and maintainability. MMCs are of particular interest to DoD for applications in which system operational temperatures exceed the capabilities of polymer matrix composites as well as for applications in which substantial weight savings can be achieved relative to typical commodity structural materials.
- High thermal conductivity composites are designed to transport heat as well as carry mechanical loads. Historically, carbon fiber development focused on aircraft structural applications where high strength and high strain to failure were the desired properties. More recently, spacecraft requirements for high stiffness, low mass, and dimensional stability provided emphasis for development of carbon based graphite fibers vital to increasing the reliability of sensitive electronic and spacecraft systems. Failure mechanisms of electrical devices and circuits of all kinds are temperature sensitive. Improved thermal performance translates to lower operating temperatures yielding higher electrical system reliability and lower operating costs. The Geosat Follow-On spacecraft uses ultra high thermal conductivity graphite fiber reinforced polymer components in the structure to meet thermal performance requirements and keep the radar altimeter within a $\pm 3^{\circ}\text{C}$ temperature range over 24 hours. Other high thermal conductivity composites are used in the solar array and propulsion module structures to help meet launch weight restrictions.

All of the military applications discussed above are applicable to the five Joint Chiefs of Staff Warfighting Capabilities. Table 1.3 summarizes the most significant ways in which specialty metals and advanced composites contribute to them.

Table 1.3 - Examples of Advanced Materials Support to Future Warfighting Needs

	I. Near perfect knowledge and communication in near real time	II. Prompt, decisive combat on a global basis	III. Minimum casualties and collateral damage	IV. Control of space	V. Missile defense and counter weapons of mass destruction
Specialty Metals	<ul style="list-style-type: none"> • Beryllium optics • High altitude endurance unmanned air vehicles 	<ul style="list-style-type: none"> • Reduced fuel consumption for aircraft • Reduced maintenance • Increased aircraft range and payload • Lightweight armored vehicles 	<ul style="list-style-type: none"> • Extended standoff cruise missiles 	<ul style="list-style-type: none"> • Launch and space vehicle tankage and structure 	<ul style="list-style-type: none"> • Beryllium optics and guidance support structure
Composites	<ul style="list-style-type: none"> • High endurance unmanned surveillance vehicles • Smaller, lighter less expensive satellite buses • Improved thermal management and reliability of high power electronics 	<ul style="list-style-type: none"> • Lightweight ground combat vehicles • Increased aircraft payload • Reduced maintenance and logistics support 	<ul style="list-style-type: none"> • Low observability • Improved armor systems 	<ul style="list-style-type: none"> • Reusable launch vehicles • Hardened spacecraft structures 	<ul style="list-style-type: none"> • High stiffness kill vehicle structure • Hypersonic interceptors

1.3 Potential Advanced Materials Concerns

As stated earlier, the Dual Use Strategy attempts to put greater reliance on the use of commercial technologies, products, and processes to further the Department's goal of moving away from separate defense and commercial industrial bases to an integrated national industrial base for meeting military requirements. While there are many opportunities for DoD to use commercial markets to satisfy its requirements for advanced materials, there are, however, concerns that commercial industry will not be able or willing to satisfy all military needs in the future.⁹ This assessment was conducted to identify potential shortfalls in meeting military requirements in light of such concerns.

Characteristics usually associated with successful commercialization in consumer and industrial markets typically include low price, high volume production, and consumer oriented performance. Military and space applications, which have made the United States a world leader in advanced materials, are characterized by just the opposite -- high cost, low volume, custom made structures far from everyday use. Reductions in and stretchouts of DoD procurements have, therefore, raised concerns about the viability of the U.S. advanced materials industrial base

⁹ These concerns were reflected by an industry review group convened by the Institute for Defense Analyses in support of this effort as well as in a businessman survey documented in *Bringing Advanced Materials to Market*, by Arden L. Bement, Jr., Said K. El-Rahaiby, and Christian X. Campbell, DoD Ceramics Information Analysis Center, April 1995.

that underlies the present and future technological superiority of U.S. military hardware. These concerns are two-fold. There are concerns about (1) the capability of the industrial base to continue to meet defense requirements for those advanced materials that have already been commercialized, and (2) assured, affordable access to the emerging advanced materials necessary to sustain U.S. military technological superiority into the future.

Several additional factors contribute to these concerns.

- **Potential Low Demand:** There are two factors that tend to lower industrial demand for advanced materials: (1) their high price relative to those of more common commodity materials and (2) because of the general unavailability of substitutes with comparable performance characteristics, there is potential for leverage by advanced material suppliers on a company that has incorporated advanced materials in its products.
- **International Competition:** Many foreign companies (sometimes with the encouragement of their government) have invested heavily in R&D and production facilities for consumer oriented products using advanced materials. This strong market presence has diminished the incentives for U.S. companies to compete commercially or even enter a niche market, e.g., advanced ceramics.
- **Lengthy, Expensive Commercialization Process:** Commercialization of new materials has historically been a difficult and expensive process.¹⁰ For example, while the demonstration of components is important in building the confidence of potential users, the process is costly and frequently components are not fabricated in sufficient quantities to accurately define costs. A recent article on the commercialization of new materials noted there is typically a 20 year time span between discovery and commercialization of a new material.¹¹ The article illustrates how the 20 year time span significantly lowers the expected financial return. It also shows how that time span makes companies more vulnerable to competition as a result of the expiration of the original patents. These issues reinforce each other to make commercialization of a new material a rather risky proposition in comparison to other investment opportunities available to industry. The business risks associated with commercializing and the limited usage of emerging forms of advanced materials therefore combine to produce a situation where industry is reluctant to invest heavily in R&D.
- **Inadequate Manufacturing Know-How:** A closer relationship between customer and supplier may mitigate some of these effects. With many advanced materials, suppliers can tailor production and marketing to exploit the possible reduction in overall design and manufacturing costs for industrial users. Progress in automation is needed to achieve more of these closer relationships as well as

¹⁰ Ibid.

¹¹ T.W. Eager, "Bringing New Materials to Market," *Technology Review*, February/March 1995, pp. 43-49.

for the development of more applications. As a result of government efforts, U.S. companies are at the leading edge in understanding the functioning and design of advanced materials of all types. However, U.S. industry has yet to develop an understanding of the manufacturing processes and controls necessary to produce advanced materials cost effectively for specific applications.

1.4 Assessment Organization

All of these concerns about the commercial advanced materials industrial and technology base raise questions about the early, assured, and affordable access to the advanced materials necessary to meet military requirements. Consequently, this study was initiated to identify the extent to which these questions of access are serious enough for DoD to consider taking possible actions.

To concentrate greater resources on more important subjects, an iterative assessment approach was taken. Initially, first cut assessments were conducted for each of the industrial bases of the three specialty metals and four advanced composites. If no serious potential issues of access were uncovered, no further assessment was undertaken. If any issues remained unclear on the basis of the initial work, those issues were iteratively studied in more depth.

Because of this iterative approach, the assessments are documented in this report in varying levels of detail. However, the general format used to document each assessment is the same. Initially an overview is presented which describes the advanced material in general terms and states *a priori* concerns. To examine these concerns, the next three sections present the data used to make the assessment: the second section describes military and commercial demand; the third section describes the industry itself; and the fourth section describes government programs for the advanced material. The final section presents the assessment findings.

The remainder of this report is organized as follows:

- Chapter 2 is the specialty metals assessment.
- Chapter 3 is the advanced composites assessment.
- Chapter 4 summarizes the conclusions from Chapters 2 and 3.

CHAPTER 2: SPECIALTY METALS

This chapter describes the specialty metals market and industrial base. It is divided into three sections -- Section 2.1 focuses on superalloys, Section 2.2 analyzes titanium, and Section 2.3 examines beryllium. All of these materials are currently in production and all are enabling materials for specific military critical applications. Superalloy products are critical to military and commercial gas turbine engines for their outstanding high temperature strength and oxidation resistance, or enable weight efficient structures at more moderate temperatures. Titanium is also vital to turbine engines as well as airframes, where it is used in critical, highly loaded and high temperature components and for the compatibility required for the metal parts of composite airframes. Titanium is important for ship sea water systems and other specialized naval uses, and is vital to front line armored systems. Beryllium is critical to many specialized military applications, notably for its properties such as low density, high stiffness-to-weight ratio, and thermal conductivity which make it particularly important to the performance of a wide range of air, sea, land, and space systems.

2.1 Superalloys

2.1.1 Superalloy Overview

The term "superalloy" encompasses metal alloys used primarily at elevated temperatures. Superalloys typically have nickel, cobalt, iron, and chromium in various combinations as their major constituents. The alloys have outstanding high temperature strength and oxidation resistance. In addition to the elements cited, typical alloys usually contain specified amounts of columbium, tantalum, molybdenum, tungsten, hafnium, aluminum, titanium, or rhenium as well as minor amounts of other added elements, plus impurities.

Superalloys represent "traditional" materials which have shown incremental improvements in properties over the years in order to remain on the cutting edge of materials technology. The current state of the art permits the use of superalloys in aircraft gas turbines which operate at turbine inlet gas temperature of 2600°F (somewhat lower for ship propulsion gas turbines). Future engines under development are expected to operate with inlet temperatures about 300°F higher. These alloys and temperatures will probably be the limit for metal gas turbine components.

The scope of the "superalloy industry" is generally interpreted to include first and second melters of raw materials and scrap who produce refined ingot, billet or slab; primary fabricators who produce castings, primary products such as powder, initial billet, bar, slab or plate; secondary fabricators who produce mill products, forgings and net shape products and manufacturers of parts for gas turbine engines and other industrial components. Thus the superalloy industry composition is somewhat broader than, for example, the steel industry, which

is never defined to include the parts manufacturers. Superalloys should not be confused with "specialty steels."

U.S. producers of superalloys are apprehensive due to a decrease in orders, new foreign production capacity, obsolescence of production equipment, and inability to either modernize or conduct adequate R&D because of capital shortages.¹ Reduced global demand for superalloys by the aerospace industry has led to about a 50 percent reduction in volume since 1991. Because of the current overcapacity for the production of superalloy semi-finished products and finished parts, there has already been a reduction in U.S. producers as well as consolidations and buyouts by foreign companies. Recent changes in capacity due to decreased engine orders in U.S. include:

- American Welding - closed
- Arwood Casting - closed
- Carlton Forge/Arcturas - consolidated
- Cytemp - closed
- CytempArmco - ceased production
- Ladish-Pacific - closed
- Reisner - closed
- Wyman/Cameron - consolidated

Therefore this technology assessment was conducted to identify potential issues of assured, affordable military access to superalloys in the future.

2.1.2 Superalloy Demand

The aerospace industry (both military and civil) consumes most of the U.S. superalloy production. There are no feasible substitutes. Aerospace applications include aircraft skins, spacecraft structures, and gas turbine engines. The gas turbine engine has a multitude of superalloy parts in the compressor and the hot section of the engine including:

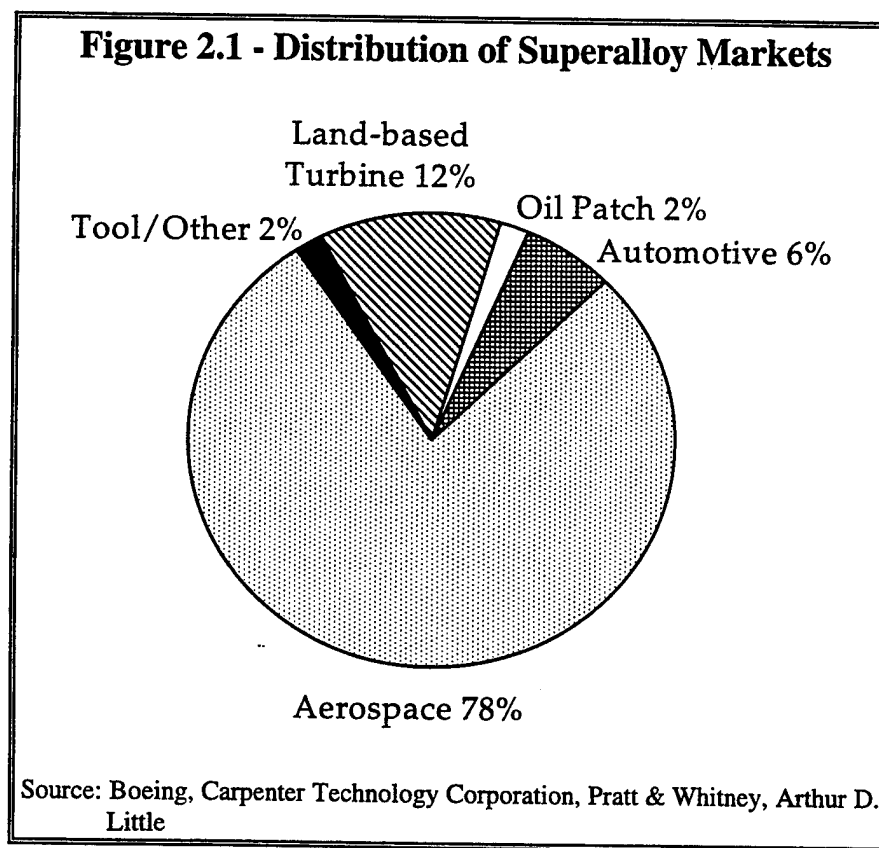
- | | | |
|--------------------|-------------------------------------|----------------------|
| • Blades and vanes | • Integrally bladed rotors (blisks) | • Combustion chamber |
| • Bearing housing | • Stators | • Flame holders |
| • Frames | • Spacers | • Afterburners |
| • Cases | • Diffuser | • Shafts |
| • Disks | • Fuel spray bars | • Exhaust nozzle |

¹ Industry representatives reported at a National Materials Advisory Board (NMAB) workshop in August 1994 that decreased profitability in superalloy production resulted in industry consolidation, reduced capital expenditures for improved processing, technology and equipment, as well as cutbacks for R&D on processing and alloy development and lower cost production methods.

Superalloys have also been used for their corrosion resistance in nuclear reactors. In the commercial market superalloys are used in:

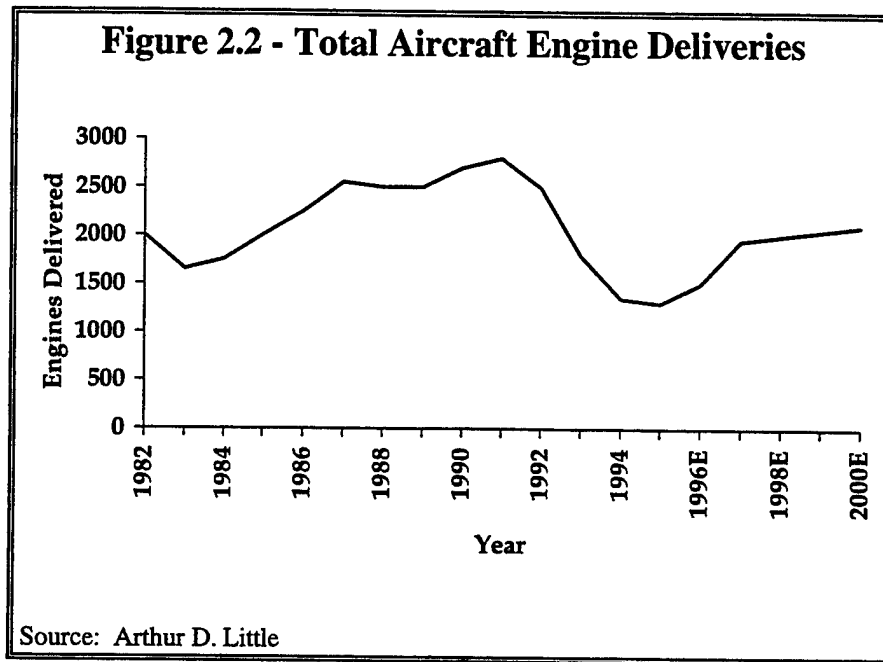
- Cryogenic applications
- Orthopedic and dental prostheses
- Petrochemical production
- Pollution control equipment
- Land based gas turbines
- Pulp and paper production
- Pharmaceutical equipment
- Food processing
- Marine
- Chemical industry
- Automotive
 - Exhaust systems
 - Valves
 - Catalytic converters

Many of the above commercial applications take advantage of the corrosion resistance properties of the alloys more than their high temperature tolerance. Total non-aerospace applications are about 22 percent of current usage, as shown in Figure 2.1.



Quantitative demand estimates for superalloys are difficult to obtain. The industry and its association do not publicly release statistics. There are no Harmonized Tariff System numbers for superalloys and except for limited data on nickel-base alloys, the Bureau of Mines, Department of Commerce, and U.S. Customs Service do not publish tonnage information on superalloy production, consumption, imports, exports, etc. However, total aircraft engine deliveries can be used as a proxy for military and aerospace demand. Figure 2.2 provides an

estimate of such data. Note the projected recovery through 1997 followed by a much more gradual increase in demand.

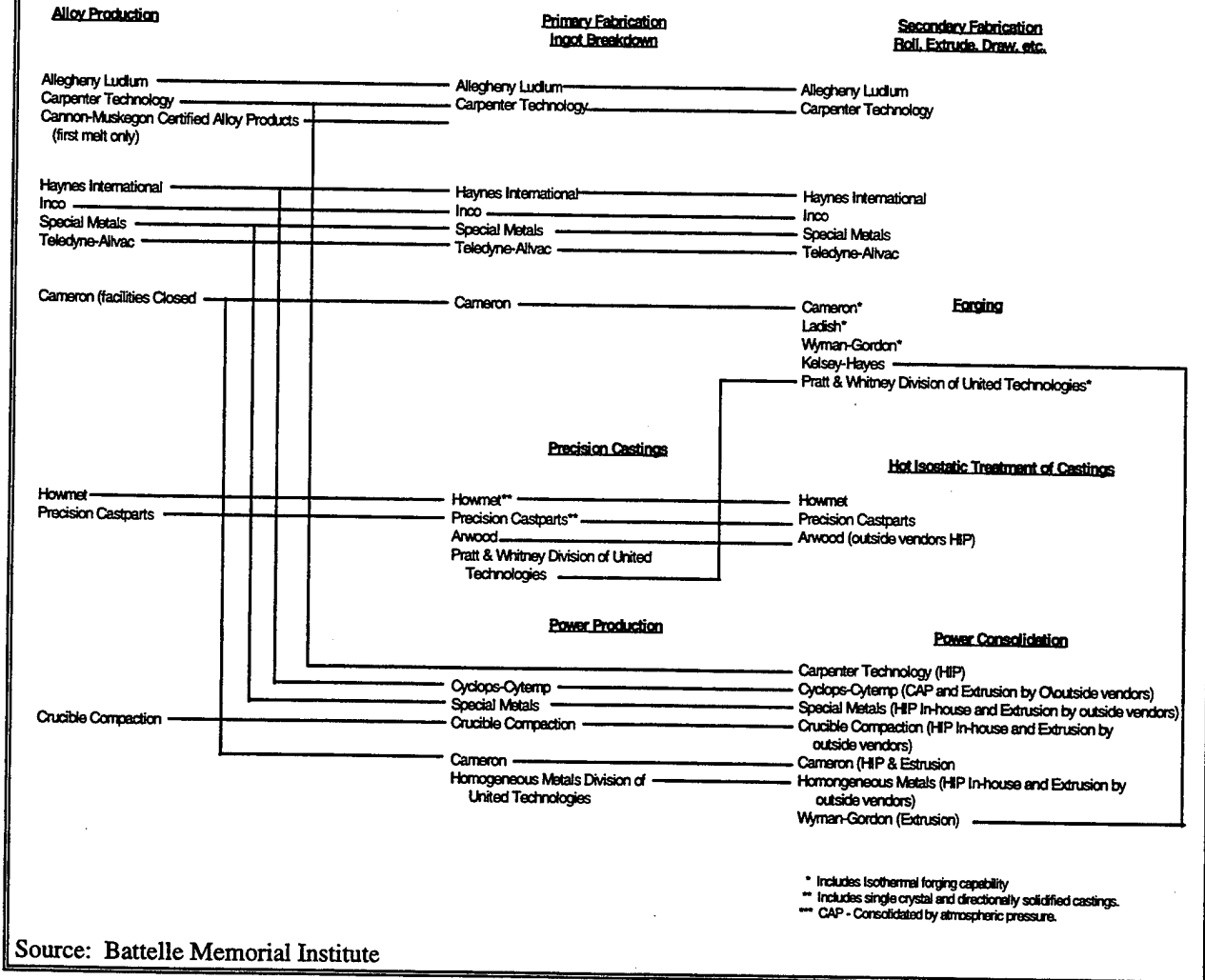


2.1.3 Superalloy Industry

The United States has been a world leader in research and development as well as production of superalloys qualified to exacting standards for use in aeropropulsion systems. The United States is a net exporter of various forms of these alloys to Europe and other gas turbine producing countries.

The structure of the U.S. superalloy industry is illustrated in Figure 2.3. Estimates of world production capacity for superalloys are difficult to establish since processes and facilities identified with superalloy production can be utilized for production of other alloys. For example, vacuum induction melting, vacuum arc remelt, electroslag remelt, inert gas or vacuum powder atomization, electric furnace (arc or induction), air melting, argon-oxygen decarburization facilities, plasma or electron beam remelt refining furnaces, continuous casting systems, open and closed die forging presses, rolling mills, numerically controlled machine tools, isostatic presses, extrusion presses, etc., can all be used in the "specialty steel" industry. However, equipment for directional solidification and single crystal casting are unique to superalloys. This technology is extremely important to the superalloy industry.

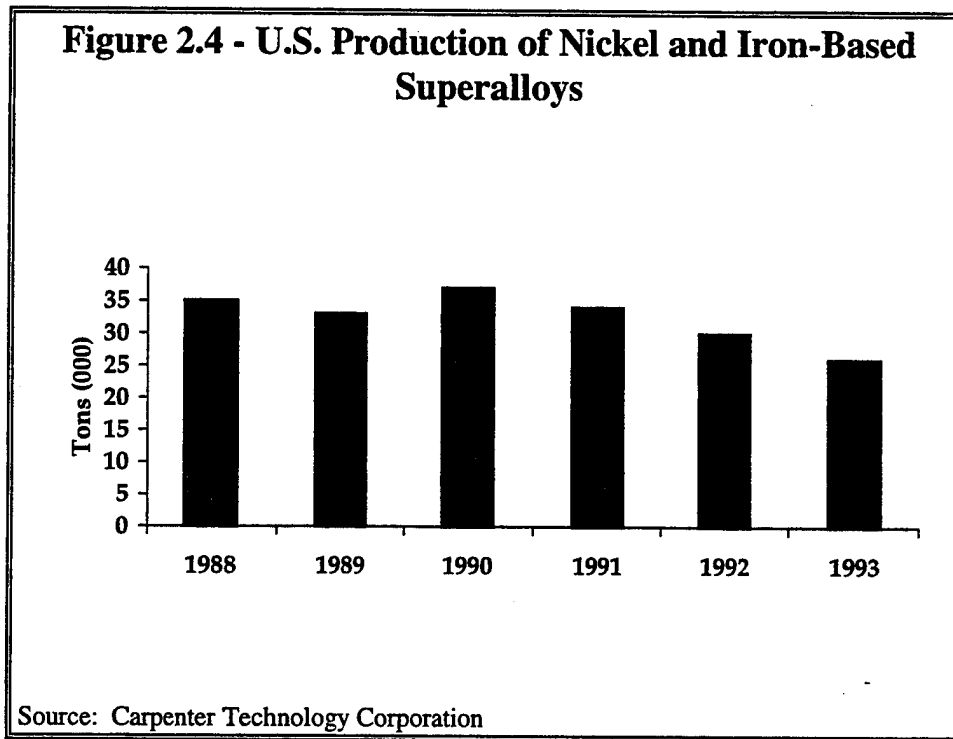
Figure 2.3 - U.S. Superalloy Industry



Published estimates of U.S. primary product production (all forms) vary from 50 million to 150 million pounds per year. However, according to G. Maurer of Special Metals Corporation, the production of premium grades of superalloys that are made to rotating grade² specifications are the most critical for aeropropulsion applications. He estimates U.S. production of premium grades is around 30 million pounds per year. U.S. first melt capacity could be as much as 200 million pounds per year exclusive of capacity available for precision castings and powder production. A recent presentation by Carpenter Technology Corporation at the National Materials Advisory Board (NMAB) in the summer of 1994 provided the data in Figure 2.4.

² Rotating grade refers to the high fracture-toughness, essentially defect-free material qualified and certified for rotating (as opposed to static) parts of gas turbine engines.

These values for wrought products should be approximately doubled to include casting production.



Foreign capacity and competition outside of the Former Soviet Union (FSU) have been increasing, primarily due to expansion of foreign aircraft production and offset arrangements by U.S. aircraft and engine manufacturers to purchase materials offshore. A recent addition to the foreign superalloy ingot production capacity is the nickel-base alloy melt shop in Australia created by a partnership agreement sponsored by Pratt & Whitney Aircraft Company. This joint venture, Western Australia Specialty Alloys, has begun production of nickel-base superalloy ingot which will be shipped to the U.S. for forging. Total foreign capacity, excluding FSU, has been estimated to be about 35 percent of U.S. capacity. Reliable estimates of FSU capacity, production or consumption of superalloys have not been obtained.

A key issue concerning foreign suppliers is that many of them have not been "qualified" to provide the specification material essential for defense and aerospace applications. Specification products, parts, and materials refers to raw and semifinished ingot, powder, sheet, bar, forgings, castings, etc., and parts made therefrom which are produced to meet the rigid government commercial or company specifications required for use in military systems for long life, high performance, and low maintenance. Qualification to meet these specifications therefore has implications for safety, reliability, liability, and guarantees. The process to obtain qualification is both lengthy and expensive.

2.1.4 Superalloy Government Programs

The U.S. Government has had a substantial impact on the development of the superalloy industry, especially through steady funding of R&D in alloy development, design criteria, processing and production. Government programs have included projects such as isostatic pressing, vacuum induction melting, vacuum arc remelting, powder metallurgy, rapid solidification, directional solidification of castings, single crystal growth, coatings, standardization and product evaluation, qualification and certification for military use (particularly rotating parts).

Over the years these government directed or supported developments have taken the superalloy industry from the vitalium dental alloy used in World War II torpedo turbines to the highly sophisticated single crystal superalloy turbine blades which are state of the art today.

It is difficult to estimate government spending on material developments since they are so closely linked to, and often included in, the costs of the gas turbine engines which use them. Currently, government programs are estimated at under \$2 million per year, with the major efforts being coatings and alloys for the Integrated High Performance Turbine Engine Technology (IHPTET) program.³

2.1.5 Superalloy Assessment

U.S. producers of superalloys are apprehensive due to a decrease in orders, new foreign production capacity, industry consolidation, obsolescence of production equipment, and inability to either modernize or conduct adequate R&D because of capital shortages. Therefore this technology assessment was conducted to identify potential issues of assured, affordable military access to superalloys in the future.

This assessment found that while further shrinkage of the superalloy industrial base may occur as supply and demand are brought in line and as foreign competition increases, there are currently no issues of assured, affordable access to meet defense requirements. Mitigating factors include: (1) for a portion of the superalloy industry, many of the companies that produce superalloys also produce specialty steels with the same facilities; (2) the military aerospace specifications appear to be sufficient to keep qualified suppliers in a niche market; and (3) many foreign competitors have not met the necessary specification qualifications and are thereby excluded from competition -- even if they were to obtain them, no immediate issues of access would arise.

³ Advanced composites are also part of the IHPTET program as discussed in Chapter 3.

2.2 Titanium

2.2.1 Titanium Overview

The titanium industry consists of titanium metal producers as well as secondary fabricators. Titanium products are essential to military and commercial gas turbine engines and to both military and commercial aircraft structures, where their applications are generally in critical, highly loaded components requiring corrosion resistance and relatively good high temperature capability.

Worldwide titanium capacity is decreasing. The large current overcapacity, particularly in the FSU, has had a serious impact on the titanium industry. Ten years ago there were 11 sponge plants operating worldwide; today there are only six -- two each in the United States, Japan, and the FSU. Recent closings occurring in the industry include:

- ILM (melting, forging, extrusions), U.S.
- Howmet (melting), U.S.
- RMI (sponge), U.S.
- IMI (sponge), UK
- Showa Denko (sponge), Japan
- Zaporozhe (sponge), Ukraine

In light of the combination of importance of titanium to DoD and the depressed global market including closings and mergers, this assessment was undertaken to identify potential issues concerning the assured, affordable access to titanium to meet military needs.

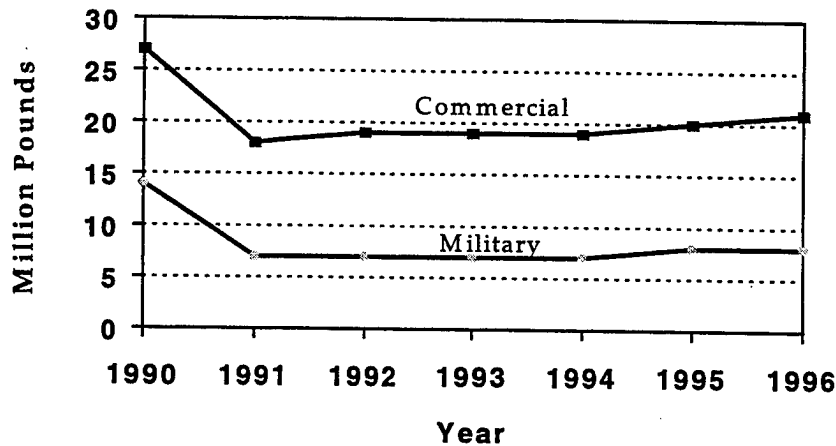
2.2.2 Titanium Demand

The aerospace industry accounts for approximately 70 percent of the U.S. market for titanium metal products, with a variety of non-aerospace commercial markets comprising the balance. Approximately 30 percent of the aerospace use is military and the remaining 70 percent is commercial. The titanium content of selected aerospace systems are shown below:

- | | |
|--------------------------------|------------|
| • F-100 current fighter engine | 41 percent |
| • F-22 airframe | 37 percent |
| • F-119 future fighter engine | 40 percent |
| • Boeing 777 engine | 28 percent |

Figure 2.5 shows the U.S. aerospace market for titanium. As can be seen, few changes are projected between 1991 through 1996.

Figure 2.5 - U.S. Aerospace Market for Titanium



Source: RMI Titanium

Specific examples of military aerospace and other uses of titanium products are shown below:

- Gas Turbine Engine Components: low pressure compressor disks and blades, inlet cases, compressor cases, hubs, spacers, fan blades and disks, struts, ducts, and fairings. Such titanium components are used in engines for the B-1, B-2, C-17, F-15, F-16, F/A-18, and KC-135 aircraft.
- Airframe Components: forgings, extrusions, plate, sheet, springs, fasteners, fail safe straps, and hydraulic tubing. These are required for the B-1, B-2, C-17, F-15, F-16, and F-117 aircraft. Titanium structural castings are being considered for the F-22 program.
- Missiles and Space Vehicle Components: cryogenic pressure vessels for liquid fueled missiles; storage tanks for cryogenic fuels and structural components of space vehicles designed to operate in cryogenic temperatures of space; rocket motor cases; nozzle exit cones; control mechanisms including servo valves, gyroscope, gimbals, housing, and tubes for communications devices; miscellaneous components including interstage structures, adapter rings and skins; space telescope frame; and turbine wheels.
- Ordnance Components: tank treads, hatches, mortar base plates, armor, rocket launcher tubes, covers, decks, blow-off panels, and power trains.

- Marine Applications: valves, pumps, piping, deep diving submersible hulls, buoyancy spheres, torpedoes, mines, propellers, deck fittings, and buoys. Because of its corrosion resistance, the Navy is using titanium for piping in seawater systems in all new ships and for some scheduled replacements of existing systems.

In addition to commercial analogs of the above, other commercial applications of titanium include:

- | | |
|---|---------------------------------------|
| • Chemical processing | • Waste processing and disposal |
| • Pulp and paper manufacturing | • Sports equipment manufacturing |
| • Textile manufacturing | • Ground transportation manufacturing |
| • Mining and minerals processing industry | • Medical related manufacturing |
| • Metal processing | • Oil and gas well drilling |
| • Petroleum refining | • Surgical implants |
| • Fire pumps | • Boat building |
| • Food and drug manufacturing | • Electroplating |
| • Electricity generation and other energy related functions | • Water purification processing |

The use of titanium in these industrial equipment and commercial products is largely related to its excellent corrosion resistance. Increased commercial demand for titanium is expected in the aerospace market. In other commercial applications, demand growth will be more gradual.

Any significant growth in commercial demand for titanium would be tied to a significant reduction in price. The Charles River Associates⁴ has developed a model for predicting commercial sales elasticity. The model predicts that a 40 percent price reduction could increase total sales by a factor of three. Such a price reduction could also significantly increase military demand.

2.2.3 Titanium Industry

Titanium production is comprised of four main processes -- chlorinating titaniferous raw materials, metallothermic reduction by reaction with magnesium or sodium, reprocessing the reactant, and recovery of titanium sponge. Major U.S. companies and their role in the overall industry are listed in Table 2.1.

⁴ "Workshop Presentation on Critical Issues for the Aerospace Specialty Metals Industrial Base", National Materials Advisory Board, July-August 1994.

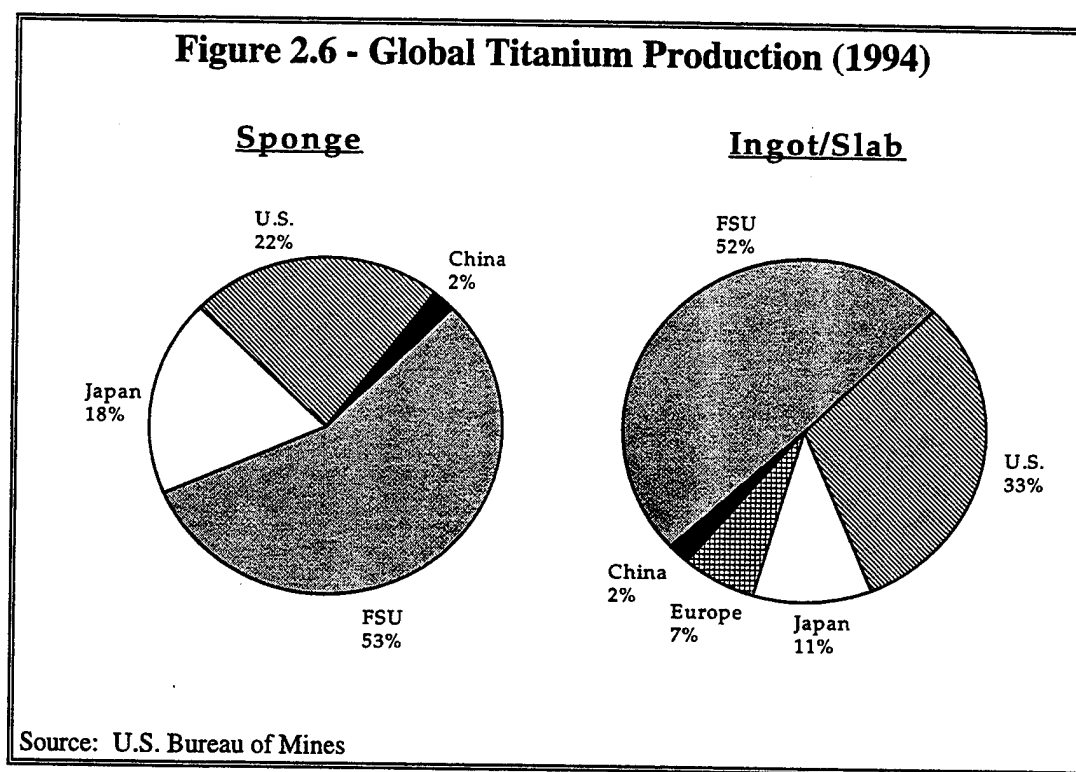
Table 2.1 - Participants in U.S. Titanium Industry

SPONGE	PRIMARY FABRICATION INGOT	SECONDARY FABRICATION MILL PRODUCTS
<ul style="list-style-type: none"> • Oregon Metallurgical (Oregon Titanium) • Titanium Metals Corp. 	<ul style="list-style-type: none"> • Axel Johnson Metals, Inc. • Howmet Corporation Titanium Ingot Division • Oregon Metallurgical • RMI Titanium Co. • Teledyne Allvac • Teledyne/WahChang • Titanium Metals Corp. • Viking Metallurgical • Wyman Gordon/Cameron Co. • Titanium Hearth Tech. 	<ul style="list-style-type: none"> • Ancotech, Inc. • Astro Metallurgical • Carlton Forge/Arcturas • Curtiss-Wright • Dynamet, Inc. • G.O. Carlson • Haynes International • Ladish Co. • Lawrance Aviation • NF and M International • Oregon Metallurgical • Precision Rolled Products • Press Forge • RMI Titanium • Sandvick Special Metals Corp • Teledyne Allvac • Teledyne/WahChang • Teledyne Rodney Metals • Titanium Metals Corp. • Viking Metallurgical • Western Pneumatic Tube Co. • Wyman Gordon/Cameron Co. • Crucible • Dynamet Technologies • Ulbrich CRES and Spec Mtl
OTHER	CASTINGS	FORGING
<ul style="list-style-type: none"> • Amermet Corp. • NF and M International • Reading Alloys Inc. 	<ul style="list-style-type: none"> • Hampton Casting Div. • Howmet Turbine Components Corp. • IMI Titanium Pomona Operation • Oregon Metallurgical • Precision Cast Parts • REM Products Div. • Tiline Inc. • Wyman Gordon Investment Castings • Schlosser Forge 	<ul style="list-style-type: none"> • Carlton Forge/Arcturas • Press Forge • Schultz Steel • Viking Metallurgical • Wyman Gordon/Cameron Co. • Alcoa Forged Products • Schlosser Forge
	POWDER PRODUCTION	POWDER CONSOLIDATION
	<ul style="list-style-type: none"> • Atomergic Chemicals Corp. • Consolidated Astronautics • Clevite • Morton International Ventron Div. • Western Zirconium Div. Westinghouse Electric Corp. • Nuclear Metals, Inc. 	<ul style="list-style-type: none"> • Dynamet Powder Products • Crucible Compaction Metals • Powder Alloy Corp.

The U.S. currently exports titanium wrought products, ingot castings and a substantial quantity of scrap. In the past, total titanium exports normally exceeded imports. In 1993 however, imports slipped ahead of exports because of imported scrap and sponge. Sponge imports grew dramatically in 1994 to total 6,470 metric tons for the year. This pattern of significant sponge imports continued into 1995. The principal sources of imported sponge remain Russia and Japan. Sponge is the largest U.S. import, followed closely by scrap and

waste. Scrap is the largest U.S. export.⁵ Europe produces no sponge and only small amounts of ingot and billet, principally in the UK, France, and Russia. Europe and Japan are the largest consumers of exported U.S. titanium.

The U.S. Bureau of Mines estimated the 1994 world production capacity for titanium sponge at 130,000 metric tons, with Russia accounting for more than half of that total, and the U.S. second with roughly a quarter of world capacity, followed closely by Japan. Excluding the U.S., actual world wide sponge production totaled 37,000 metric tons in 1993 and 31,000 metric tons in 1994 -- significantly under capacity. Figure 2.6 portrays the global distribution of titanium sponge and ingot/slab production.



Domestic sponge consumption for the period 1983-1994 ranged from 25,000 metric tons down to 14,000 metric tons. Sponge consumption peaked in 1989 at about 25,000 metric tons, declined slightly in 1990, followed by a steep decline to about 14,000 metric tons in 1991. The pattern from 1991 through the present is one of slow growth to about 16,500 metric tons in 1994. Imports of sponge and scrap are playing a significant role in the depressed state of U.S. sponge

⁵ There are a number of reasons for both imports and exports of U.S. scrap: a specific grade of scrap is preferred over another; only a handful of companies in the titanium business process scrap; and scrap is often used in steel and other alloys.

production.⁶ Russian imported sponge was selling for about \$1.30 a pound in 1993, well below the production price of U.S. sponge offered for \$4.00 a pound. 1995 published prices for U.S. sponge range from \$3.75 to \$4.25 a pound. However, current Russian prices have risen to the prevailing market value, and therefore U.S. sponge production is no longer at a competitive disadvantage.

Production of titanium mill products follow a pattern related to sponge. Mill product production peaked in 1989 at 30,000 metric tons, with a fall to 17,900 metric tons in 1994. Shipments of mill products show a similar decline from 25,000 metric tons in 1989 to a low of 15,600 metric tons in 1991. While titanium casting production data are not available, shipments of castings have grown from 200 metric tons in 1983 to a peak of 600 metric tons in 1991 -- shipments were about 500 metric tons in 1994.

In summary, the following observations by the National Materials Advisory Board 1994 Workshop on Aerospace Specialty Metals, along with recent developments, reflect the status of the titanium industry:

- Consolidation of the domestic industry, including closings and joint ventures (mergers), has been extensive. The industry as a whole is expected to be marginally profitable in 1995.
- The military aircraft titanium market is permanently reduced. Army and Navy demand for non-aerospace applications may grow in the future, especially if prices are reduced.
- The commercial aerospace market is also down, at least for near term.
- Excess capacity brought by the FSU is probably here to stay; world wide industry capacity outstrips demand.

Facility modernization is necessary to reduce titanium costs to a level sufficient to open major new demand opportunities. The Army has undertaken efforts to reduce plate cost by concentrating on reducing the use of sponge, reducing melting costs, and eliminating some of the surface preparation and clean-up. While these efforts are not applicable to aerospace grades of titanium, they do apply to most other uses of titanium.

Cold hearth melting processes have been suggested as a means of halving melting costs for aerospace grade titanium. The use of continuous processing has the potential to reduce fabrication cost considerably.

The titanium industry has not made investments to implement any of these changes. Even if combined, all of these initiatives are thought to be insufficient to achieve the price reductions necessary for major increases in military and commercial demand. More research into low cost processes would be required.

⁶ Scrap can replace sponge in the production of titanium ingot. Currently, scrap is used for approximately 50 percent of the feed for ingot production.

2.2.4 Titanium Government Programs

The development of the U.S. titanium industry was initiated and fostered by government actions. Starting with the Bureau of Mines support of the Kroll process development in the 1940s,⁷ government R&D and procurement have supported alloy development, design criteria, and processing and production initiatives. Of particular importance has been the work directed or supported by DoD in evaluation, characterization and standardization of alloys and processes including welding, diffusion bonding, extrusion and the myriad potential and realized hardware applications in aerospace, marine and battle environments.

Over the years, these government directed or supported developments have placed the U.S. titanium metal industry in its present prominent world position. While the FSU production of titanium metal exceeds that of the U.S., the U.S. continues to excel in the quality of its products and alloy development. It is difficult to estimate the costs to the government of material developments since they are so closely linked and often included in the costs of the engine, airframe, armored vehicle, and marine and other hardware developments which use them. Currently, government programs are estimated at under \$3 million per year, with major efforts focusing on titanium aluminides for high temperature use, titanium foams, low cost titanium airfoils and structural armor, rapid prototyping and the application of the Osprey sprayed metal process for marine hardware.⁸

The Army has budgeted \$200,000 in FY 1996 for a Low Cost Titanium Program. The general goals are to utilize lower cost melting practices and relaxed chemistry specifications to produce lower cost titanium. The Army goal is to obtain titanium in the \$6 to \$7 per pound range. This is not a material development program. Its purpose is to evaluate the lower cost material. If the program demonstrates that the lower cost materials have the required properties, the Army hopes to replace approximately 3500 pounds of steel with approximately 2400 pounds of titanium on 120 vehicles.

2.2.5 Titanium Assessment

In light of the combination of importance of titanium to DoD and the depressed global market including closings and mergers, this assessment was undertaken to identify potential issues concerning the assured, affordable access to titanium to meet military needs.

Despite issues of decreased demand and excess capacity, no immediate concerns regarding assured access were found. In real terms, titanium prices are less than they were five

⁷ The Kroll process involves the reduction of titanium tetrachloride by magnesium metal to produce titanium sponge and byproduct magnesium chloride. Pilot work was conducted by the Bureau of Mines in 1938.

⁸ A process whereby molten titanium is sprayed onto a sacrificial mandrel.

years ago. However, if prices could be reduced by approximately 40 percent, new military demand may emerge. Such a reduction in titanium prices would not only make titanium less expensive to DoD but also help producers expand their commercial markets. To achieve this 40 percent price drop, significant facility modernization along with new research into low cost processes are necessary. However such efforts must be the responsibility of industry, unless a specific analysis can prove that any DoD investment will pay for itself in reduced costs within a reasonable time horizon.

2.3 Beryllium

2.3.1 Beryllium Overview

Beryllium is produced and sold in three forms -- metallic beryllium, beryllium alloys, and beryllium oxide. Approximately 15 percent of annual U.S. beryllium consumption is for metallic beryllium products. The inherent physical properties of metallic beryllium such as light weight, high stiffness, transparency to X-rays, neutron reflection, and dimensional stability over a wide temperature range make it an ideal choice of material for the following applications:

- Satellite and space vehicle structures
- Inertial guidance systems
- Military aircraft brakes
- Space optical system components
- X-ray windows
- Nuclear reactors and weapons
- High speed computer components
- Audio components
- Laser mirrors
- Electro optical systems
- Neutron moderator in reactor control rods
- Canning material

Beryllium-copper alloys (less than two percent beryllium) account for about 75 percent of annual U.S. consumption of beryllium products. Beryllium-copper alloys benefit from the high strength and hardness of beryllium metal, and in addition are characterized by high electrical and thermal conductivity, good corrosion and fatigue resistance, and nonmagnetic properties. Because of these properties, beryllium-copper alloys are used as follows:

- Springs, connectors, and switches in automotive, aerospace, telecommunications, and radar, factory automation, home appliances, instrumentation and control systems applications.
- Tubing for oil and gas drilling equipment
- Bushings and bearings in aircraft landing gear and heavy machinery
- Fiber optic telecommunications rods
- Wire for joining integrated circuits to printed circuit boards
- Resistance welding electrodes
- Machinery components and materials handling systems
- Molds for glass, metal and plastic components

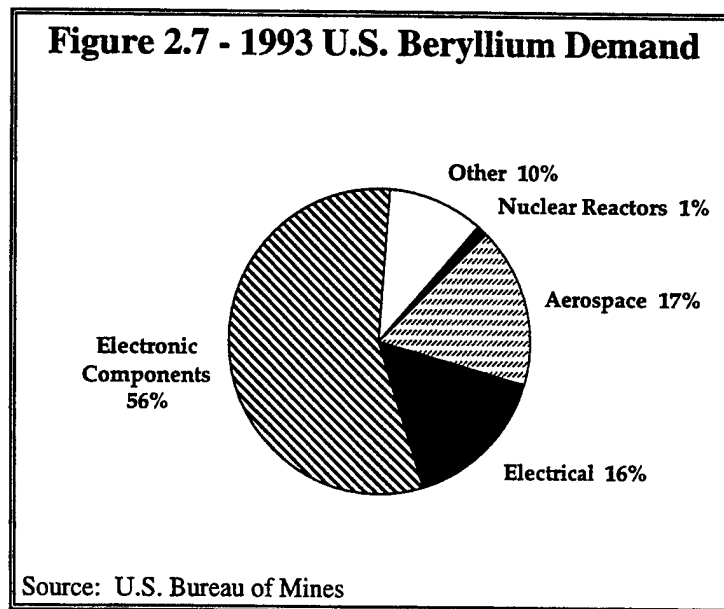
Beryllium oxide consumption averages about 10 percent of total domestic beryllium consumption. Beryllium oxide is also characterized by the high strength and hardness properties associated with beryllium metal, and is furthermore transparent to microwaves, and is an excellent thermal conductor and electrical insulator. Application areas for beryllium oxide include:

- Substrates for high density electronic circuits for high speed computers
- Automotive ignition systems
- Lasers
- Radar and electronic countermeasure systems
- Microwave communications systems
- Microwave ovens

Beryllium metal, alloys, and oxide have long been considered critical materials because of their physical and mechanical properties. With defense downsizing, there has been some concern about the possible shutdown of some production lines. Therefore, this assessment was undertaken to assess whether DoD will continue to have assured, affordable access to this specialty metal.

2.3.2 Beryllium Demand

In dollar terms, between 75 and 80 percent of beryllium consumption is used for commercial applications, up from about 65 percent in the mid 1980's. About 10 percent of metallic beryllium, 90 percent of beryllium alloys, and 70 to 80 percent of beryllium oxide is consumed by the civilian sector. Commercial demand for beryllium products (with the exception of metallic beryllium) is increasing and, to a large extent, mitigates the effects of decreasing military demand. Demand for beryllium materials in traditional applications such as electronics and telecommunications are expected to fluctuate with national economic trends. Figure 2.7 shows the distribution of beryllium demand in 1993.



DoD uses beryllium metal in a number of aircraft, missile, and satellite programs. The F/A-18, the F-22 and the LANTIRN weapon targeting pod all contain beryllium, as do the Maverick, HARM and Minuteman missiles and the Global Positioning System and MILSTAR satellites.

A significant drawback for beryllium is its relatively high price. In all its applications, beryllium products must compete with other lower cost, lower performance materials. The sharpest decrease in beryllium product demand has occurred in beryllium metal. Metallic beryllium demand averages about 15 percent of the total annual domestic beryllium demand (down from nearly 30 percent in 1988) where it was used principally in aerospace and defense applications. Since most of the cutbacks in defense applications have already occurred, anticipated demand for beryllium metal for defense and aerospace applications should remain stable, averaging 15 percent of the total annual domestic production of beryllium products. While there is a potential for increased use of beryllium aluminum structural alloys in defense and other aerospace applications, no firm requirements have been identified.

2.3.3 Beryllium Industry

The United States has long benefited from having a well established industrial base for all elements of beryllium product production and utilization, including mining, processing, and consumption. The U.S. firm Brush Wellman is recognized as the world's leading beryllium product supplier. The company is vertically integrated and thus has all the requisite facilities and trained personnel necessary to support the production of beryllium and beryllium containing products and components.

The beryllium industry has fully matured since commercial production in the United States started in the 1920s. In 1964 the U.S. became the principal supplier of beryllium products for the entire world. U.S. industry accounted for over 64 percent of world production of ore, 71 percent of world demand, and 83 percent of processing of primary beryllium products in the decade from 1981-1991. However, this domestic industry is relatively small -- about 25 people are employed in mining and extraction and another 400 in production.

U.S. consumption of beryllium (measured in metric tons of beryllium content) fluctuated for the years 1990-1993 as shown below.

<u>Year</u>	<u>Consumption</u>
1990	175
1991	203
1992	159
1993	183

NGK Metals produces beryllium oxide in the United States and beryllium-copper alloy in both the U.S. and Japan using beryllium hydroxide supplied from Brush Wellman. The U.S.

imported 11 metric tons of beryllium-copper alloys and scrap from Japan, China, and Germany in 1992. In 1993, imports of beryllium-copper alloy, beryllium oxide, and other beryllium products amounted to a total of approximately \$1.7 million, based mainly on beryllium-copper alloy imported for secondary manufacturing by NGK for the domestic U.S. market.

The FSU is the second largest beryllium producer in the world with an estimated 1990 production of 76 metric tons of beryllium (20 percent of total world mine production for that year). It is estimated that production fell to only 50 metric tons of beryllium in 1992 of which 70 to 75 percent went to the military sector.

The breakdown of the interdependent system of trade between FSU republics coupled with reduced FSU demand for beryllium products has increased the likelihood that FSU beryllium products will be offered on the world market, probably at greatly reduced prices. It has been reported by the U.S. Bureau of Mines that a joint venture between U.S. and Kazakhstan companies has been formed to market beryllium in the U.S. Aerospace and other critical applications require qualified sources of materials. To date, materials from potential FSU suppliers have not been qualified for use in such systems.

Although low priced imports from ULBA in Kazakhstan may threaten U.S. industry's ability to maintain its critical production of metallic beryllium (note: ULBA is not currently producing beryllium metal but is selling from its stockpile believed to contain 30 years worth of BeOH), the overall survival of U.S. beryllium production does not appear to be threatened, despite the downsizing of the defense industry.

A recent development could eventually support U.S. metallic beryllium production. Nuclear Metals, Inc. filed for an international patent on a new beryllium-aluminum alloy suitable for casting in September 1994. The patent covers alloys ranging from 60 to 70 weight percent beryllium with small additions of silicon and/or silver and the balance, aluminum. Mechanical properties of the new alloy are similar to annealed low carbon steel (25 thousand pounds per square inch yield strength and 30 million pounds per square inch elastic modulus) in the as-cast condition. Yield strength can be more than doubled by mechanical working (extrusion). Ductility of the new alloy family can exceed two percent in the as-cast condition and 12 percent in the extruded condition. Density of the new alloys is approximately one quarter that of steel and three quarters that of aluminum. The new alloys are claimed to eliminate segregation and microporosity problems frequently encountered in cast beryllium and, therefore, enable economic fabrication of lightweight parts via casting.

Metallic beryllium is utilized as an ingredient in the production of new alloys. Because they have promising mechanical properties and low density, a commercial market could be developed depending on price and other factors. A commercial market for these alloys would in turn help sustain the U.S. production of metallic beryllium if Nuclear Metals chooses to purchase metallic beryllium from Brush Wellman. At this time, however, Nuclear Metals' source plans, marketing plans, and production capacity for these new alloys are unknown.

Finally, a cursory overview of the business outlook for beryllium component manufacturers provided by Brush Wellman states that the outlook for primary manufacturing is guardedly optimistic and the outlook for secondary metalworking is optimistic. However, the outlook for precision machining is pessimistic for one company and only guardedly optimistic for the other, and the sole optical finishing company is facing a partial shutdown of operations. Nevertheless, no severe dangers to future DoD acquisitions are perceived.

2.3.4 Beryllium Government Programs

From its discovery in 1797, through its first metallic production in 1828 and its first commercial development in the U.S. in 1916, beryllium did not receive government support. The major thrust of government interest has been associated with nuclear reactor and weapon programs. However, beryllium-copper alloys have been investigated and characterized with government support, as well as the toxicity and use of beryllium metal in special applications such as gyroscopes.

The Departments of Defense and Energy became concerned about future availability of beryllium metal in 1979 when the last U.S. competitor to Brush Wellman closed its production facility (there had been 11 producers of beryllium metal in the mid-1970s). The two Departments established a Beryllium Coordinating Committee in 1981 to coordinate all R&D and production work to ensure complementary, not duplicative, efforts were being funded.⁹ As a separate Committee effort, \$5 million was invested with Brush Wellman to develop gas atomization for near net shape processing of beryllium metal into parts.

Currently, DoD maintains beryllium in the National Defense Stockpile (NDS). The amounts of beryllium-containing materials currently held in the stockpile are shown in Table 2.2 below:

Table 2.2 - NDS Beryllium Inventory	
Materials	Short Tons
Beryllium metal	400
Beryllium copper alloy (4 percent Beryllium)	7,387
Beryllium ore	15,023
Total	1,177
Source: 1995 Report to the Congress on National Defense Stockpile Requirements	

⁹ During the early and mid-1980s, projections for beryllium metal usage were increasing. With the breakup of the FSU, these projections did not materialize.

2.3.5 Beryllium Assessment

Beryllium metal, alloys, and oxide have long been considered critical materials because of their physical and mechanical properties. With defense downsizing there has been some concern about the possible shutdown of some production lines. Therefore, this assessment was undertaken to assess whether DoD will continue to have assured, affordable access to this specialty metal.

This study found that declines in defense markets have been offset by new applications, e.g., automotive electronics, appliances, telecommunications, plastic molds, and automotive air bag inertial switch springs. Therefore, despite weakness in some elements of the beryllium manufacturing base, the overall survival of the U.S. beryllium industry does not appear to be threatened. Furthermore, the National Defense Stockpile contains a considerable supply. Consequently, this assessment has reached the conclusion that as of now, DoD will continue to have assured, affordable access to the limited quantities of beryllium products it needs to meet its requirements.

CHAPTER 3: ADVANCED COMPOSITES

Composite materials consist of two or more constituent materials combined to produce a material having at least some properties superior to those of the individual components. Composites generally consist of fibers or particulate reinforcements embedded in a matrix material that holds the fibers or particles together, transfers loads among the fibers and provides environmental and chemical durability. Composites are typically classified by their matrix materials. Advanced composites are state-of-the-art forms of composite materials reinforced with either continuous fibers or particulates that are engineered to provide specific properties that enhance performance. This chapter examines the four classes of advanced composites. The assessments are ordered from the most mature industrial base to the least mature industrial base as follows: Section 3.1 is for polymer (organic) matrix composites (PMCs); Section 3.2 is for ceramic matrix composites (CMCs); Section 3.3 is for metal matrix composites (MMCs); and Section 3.4 is for high thermal conductivity composites.

3.1 Polymer (Organic) Matrix Composites (PMCs)

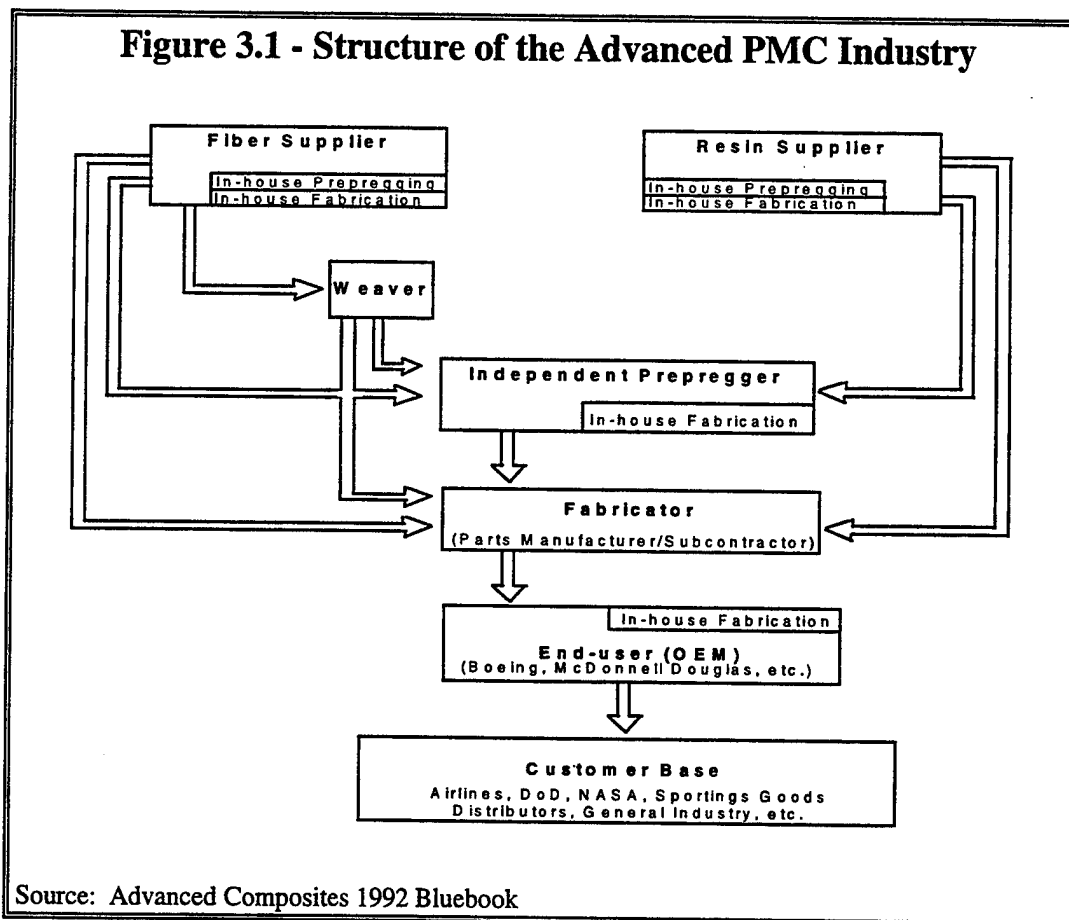
3.1.1 PMC Overview

Of these four classes of composite materials, only PMCs are currently in large scale production. Polymer (organic) matrix composites can be further subdivided into two principal categories as described below:

- (1) High Volume Reinforced Plastic Composites: These composites, also known as reinforced plastics, usually consist of lower strength, lower cost E-glass reinforcement fibers embedded in a plastic matrix. The fibers, sometimes continuous, as in a fabric or in a bundle called a tow, and sometimes chopped and randomly oriented as in a mat, provide strength and stiffness; the polymer or plastic matrix, often a polyester resin, holds the fibers together, transfers loads among the fibers and provides environmental and chemical durability. Starting in the 1940's, these reinforced plastic composites found a growing market in shower stalls, bathtubs, cafeteria trays, office wall separators and office equipment, railroad tank cars, fuel storage tanks, missile cases, boats, yachts, fishing trawlers, mine sweepers and automobile bodies (starting with the Corvette in 1954). Composites have competed successfully against wood and metals such as zinc, tin and bronze and now have a large market. The SPI Composites Institute reports that 2.5 billion pounds of reinforced plastic composites were shipped in the United States in 1992.
- (2) Advanced High Performance Polymer Composites: These PMCs employ high performance reinforcement fibers (predominantly, carbon fibers but also aramid, S-2 fiberglass, or boron fibers) for aerospace applications where outstanding

specific strength and stiffness results in weight savings of 15 to 50 percent in aerospace structures when compared to both high strength aluminum and titanium. The Air Force B-2 bomber and the Navy/Marine Corps V-22 Vertical or Short Take-Off and Landing aircraft are dependent on these advanced PMCs, and numerous other military and commercial aircraft and missiles owe much of their performance to advanced polymer composites. In 1994, world-wide advanced polymer composite prepreg shipments were about 20 million pounds.

Figure 3.1 depicts the structure of the advanced PMC industry and the customer base it serves.



The advanced PMC industry structure is generally considered to consist of the polymer resin producers; the fiber producers; the matrix resin formulators, prepreggers¹ and parts manufacturers; and the prime contractors, original equipment manufacturers, and first tier

¹ "Prepreg" (i.e., pre-impregnated) refers to an intermediate tape or cloth-like product consisting of unidirectional or woven fibers pre-impregnated with unreacted resin that can be cut, shaped, and stacked in a mold prior to curing the resin through the application of heat.

subcontractors who process, fabricate, assemble and generally serve as major system integrators of aerospace structural components.

It is the advanced high performance polymer composites industrial base which is the subject of this section. This form of polymer matrix composites provides high performance in defense systems necessary to meet DoD requirements. There has been significant recent restructuring in the PMC industry due to downturns in the military aerospace markets, reflected by plant closings and declining sales in the past few years. This assessment was undertaken to evaluate the effect of this restructuring on assured, affordable military access to advanced polymer composites technology.

3.1.2 PMC Demand

The Suppliers of Advanced Composite Materials Association (SACMA) has released industry statistics on the worldwide shipment of advanced composite materials shown below in Tables 3.1, 3.2, and 3.3.

Table 3.1 - Worldwide Advanced Composite Matrix Resin Shipments for 1989-1993		
Year	Non-Prepreg Applications (in Pounds)	Prepreg Applications (in Pounds)
1989	25,006,362	8,188,534
1990	28,159,457	7,875,267
1991	30,889,038	8,043,400
1992	31,303,202	8,041,317
1993	31,163,877	8,570,843

Table 3.2 - Worldwide Advanced Composite Carbon Fiber Shipments for 1991-1st Half 1994		
Year	Pounds	U.S. Dollars
1991	11,442,059	\$298,800,000
1992	13,002,812	\$374,100,000
1993	14,598,544	\$384,900,000
1994 (mid-year)	7,211,174	\$225,100,000

Table 3.3 - Worldwide Advanced Composite Prepreg Shipments for 1989-1993

Year	Pounds	U.S. Dollars
1989	20,202,158	\$467,500,000
1990	23,783,489	\$503,100,000
1991	26,372,306	\$493,500,000
1992	25,734,423	\$457,200,000
1993	19,849,654	\$396,000,000

It is interesting to note that, while Table 3.3 shows a four year industry decline in the dollar value of prepreg PMC shipments, the matrix resin and carbon fiber infrastructure did not experience similar declines. Table 3.4 shows 1992 and projected 2002 U.S. and world-wide shipments of advanced PMCs broken down by end use.

Table 3.4 - Estimated 1992 and Projected 2002 Worldwide PMC Demand, By End Use

End Use	Worldwide (thousand metric tons)		United States (thousand metric tons)		Rest of World (R.O.W.) (thousand metric tons)		Average annual growth rate (percent)		
	1992	2002	1992	2002	1992	2002	World	U.S.	R.O.W.
Aircraft	4.1	8.4	2.4	4.4	1.8	4.0	7.4	6.5	8.5
Missile/space	2.6	3.2	1.7	1.9	.9	1.4	2.1	1.0	4.0
Recreation	2.2	3.5	1.2	2.2	1.0	1.4	5.0	6.0	3.5
Armor	1.9	3.1	1.1	2.0	.8	1.2	5.4	6.0	4.5
Automotive	.3	2.9	-	2.6	.2	.3	26.7	50.0	2.0
Industrial/other	2.6	4.1	1.0	1.5	1.6	2.6	4.6	4.0	5.0
TOTALS	13.7	25.2	7.4	14.6	6.3	10.9	6.4	7.0	5.6

Source: Kline & Co., Inc.

The data in Table 3.4 should correspond to the data in Table 3.3 however, since the sources are different, the agreement is not absolute. Nevertheless, the data are close enough to make some inferences about military demand. In Table 3.4, military demand is composed of the lines for armor and military/space and part of the line for aircraft. Since the aircraft line has a large commercial component, the sum of only armor and military/space represents a lower bound on military demand. Therefore, according to Table 3.4, the DoD advanced PMC usage in 1992 was at least 40 percent of U.S. consumption and at least one third of world-wide demand. Although DoD's market share is projected to drop to at least 25 percent of 2002 U.S.

consumption and 25 percent of the world-wide consumption as well (because of increased commercial applications), DoD usage remains a very significant part of the market.

3.1.3 PMC Industry

Based on the overall structure of the advanced PMC industry, this section is divided into four parts: the matrix resin industry, the reinforcement fiber industry, prepreg suppliers, and fabricators.

3.1.3.1 Matrix Resins

Many types of plastic resins are used as PMC matrices. The resins used for advanced, structural PMCs are specialized forms of the polymers used for the much larger markets for conventional composites and plastics. Advanced resins are specially formulated to provide toughness, chemical resistance, and other desirable engineering properties. Composites made of advanced epoxy resins can be used at temperatures up to about 250°F, but some resins (e.g., bismaleimides and polyimides) have been developed for use at 400°F and 550°F, respectively. These latter resins are of great importance for aerospace applications where high temperature performance is required.

There are two basic types of plastic resins: (1) *thermosets* and (2) *thermoplastics*. Thermoset resins are chemically crosslinked irreversibly to form matrices while thermoplastic resins are heated and consolidated under pressure but can be reshaped and reprocessed. A common analogy is to compare thermosets to "egg white" and thermoplastics to "ice cubes." The former sets irreversibly upon heating while the latter can be melted, resolidified and remelted. Thermoset epoxies are the most commonly used type of thermoset resins for advanced PMCs. Thermoplastic resins, such as polyetheretherketone and polyphenylene sulfide, have seen more limited use so far.

There are several producers of plastic resins, and a larger number of companies that blend materials to formulate resins for particular applications:

- The largest global producer is Ciba Corporation of Switzerland, with a market share of about 10 percent. Ciba has plants in a number of countries, including a \$100 million plant built in 1989 to produce specialty resins in Alabama. This plant has the capacity to produce 7.3 million pounds of aerospace resins per year, but it is being reoriented to serve other markets (e.g., electronics). Ciba's resins (MY720 epoxy) are qualified for a number of military and civilian programs, including the Airbus. Ciba supplies basic resins to other resin manufacturers.
- Shell Oil Company also supplies a broad range of resins. Shell is Dutch and British owned but has facilities in the United States. In 1992, Shell and Ciba

purchased resin producing facilities from Rhone-Poulenc in France. Shell also owns the German resin producer Technochemie.

- British owned Imperial Chemical Company (ICI) has plants in several countries, and owns ICI Fiberite (977-3 epoxy) in Arizona.
- Other large producers in Europe include Germany's BASF and France's Roussel.
- Dow Chemical Company produces a range of specialty resins.
- DuPont produces specialty resins (K-polymer) and reportedly has considerable excess capacity as a result of defense cutbacks.²
- Other U.S. producers include Hercules (3501-6 epoxy), Hexcel (F650 BMI), and Cytec (BMI).
- Dainippon Ink and Chemicals is a large resin producer in Japan. Dainippon purchased U.S. producer Reichold Chemicals in 1987.
- Nippon Steel Chemical, Sumitomo, Toray, and Mitsubishi Rayon are other specialty resin producers in Japan.³

The principal producers, Ciba and Shell, are both large global companies for whom specialty resins represent only a minor interest. The actual demand for resins used for advanced composites is estimated to have grown a total of 20 percent between 1989 and 1993, an average of five percent per year. Growth is expected to be flat through 1995 and then five to six percent from 1996 through 2000.⁴

This industry is not concentrated and producers have facilities widely dispersed geographically. There is extensive European ownership of production facilities in the United States. Thus, DoD can benefit from the global experience of these companies, for example, Ciba's work supporting the Airbus. Major chemical companies are also active in the United States and Japan.

Production of specialty resins for advanced composites is a very small part of a very large business. In 1993, the global market for all structural thermoset resins amounted to \$3.2 billion for 3.5 billion pounds.⁵ In contrast, the market for specialty thermoset epoxies amounted to only \$96 million for 35 million pounds, and not all of this material was used for advanced composites. Furthermore, sales of the very specialized high temperature resins (e.g., polyimides and bismaleimides) amounted to roughly \$20 million for 500,000 pounds. Usage of thermoplastic resins amounted to less than five percent of the thermoset usage. The 1993 demand for specialty

² "Going from Exotic to Mundane," *New York Times*, July 1993.

³ The Japanese are developing high-temperature resins for their aerospace program. They also continue to pursue thermoplastics, for which U.S. interest has waned. Toray developed a very good tough epoxy, now used for Boeing's 777 airliner, and is working on toughened high-temperature resins. See the discussion in the Japan Technology Evaluation Center (JTEC) publication *Panel Report on Advanced Manufacturing Technologies for Polymer Composite Structures in Japan*, April 1994, pp. 30,81,223.

⁴ These estimates were presented by Ciba at the NMAB Workshop, August 1994.

⁵ This statistical description draws heavily on a Ciba presentation at the NMAB Workshop, August 1994.

resins was distributed as shown in Table 3.5.⁶ The regional shares of production were not determined.

Table 3.5 - Regional Demand for Specialty Resins (1993)		
Region	\$ Share	Weight
North America	45%	46%
Europe	25%	24%
Japan	18%	18%
Other	13%	12%

In conclusion, the specialty plastic resins industry for advanced polymer composites is a spin-off of the much larger plastics industry. The resin suppliers for advanced polymer composites are generally large chemical companies involved in high volume plastics production for which specialty resins are only a small portion of their overall business base. As a consequence, the industrial base for advanced polymer resins (thermosets or thermoplastics) is well established.

3.1.3.2 Reinforcement Fibers

Carbon fiber is the predominant reinforcement fiber used in advanced polymer composite applications. However, other reinforcement fibers which are used in military and commercial applications include aramid (Kevlar), S-2 fiberglass, and boron fiber.

Carbon Fibers

Carbon fibers are made from either polyacrylonitrile (PAN) or pitch precursor fibers. There are many types and grades of carbon fibers, varying particularly in tensile strength, tensile modulus (stiffness), thermal conductivity, and price. Some PAN-based fibers have very high tensile strength (approaching one million pounds per square inch) and modulus (40 to 50 million pounds per square inch). Pitch-based fibers have been developed particularly for ultra high modulus (greater than 100 million pounds per square inch) or high thermal conductivity (1100 Watts/meter-Kelvin). Carbon fiber is used primarily for PMCs but may also be used in MMCs.

⁶ Specialty resins used for structural thermosets include specialty hardeners and cyanate esters in addition to epoxies and high-temperature resins.

Table 3.6 identifies the principal global suppliers of PAN-based carbon fiber, with a combined 1993 capacity of 25.9 million pounds per year.

Table 3.6 - PAN-Based Carbon Fiber Capacity (1993) (million pounds per year)					
Company (Owner)	Location	Ownership	Precursor Source	Capacity	Consumption
Hercules	US	US	Self/Import Sumitomo	4.1	
Amoco	US	US	Self	4.2	
Grafil (Mitsubishi Rayon)	US	Japan	Import Mitsubishi	1.4	
Akzo Fortafil* (Akzo)	US	Netherlands/ Japan	Import Courtaulds	1.1	
Zoltek	US	US	Import Courtaulds	1.0	
Subtotal US				11.8	5.5
Toray	Japan	Japan	Self	4.9	
Toho Rayon	Japan	Japan	Self	4.4	
Mitsubishi Rayon	Japan	Japan	Self	0.7	
Subtotal Japan				10.0	2.9
Akzo Tenax (Toho)	Netherlands	Japan	Import Toho	1.4	
Soficar (Toray)	France	Japan	Import Toray	1.4	
R.K. Carbon	UK	UK	Courtaulds	0.3	
Subtotal Europe				3.1	3.2
Taiwan Plastics	Taiwan	Taiwan		0.5	
Korea Steel	Korea	Korea		0.3	
Afikam Carbon	Israel	Israel		0.2	
Subtotal Other				1.0	2.9
GRAND TOTAL				25.9	14.5
Source: Presentation by Mike Michno at August 1994 NMAB workshop and Carvalho, May 1993, p. 16.					
* An additional production unit with a capacity of 3,000,000 pounds per year is under construction (SAMPE, Vol. 40 (1995), p. 996).					

Most capacity is located in the U.S. (46 percent), Japan (39 percent), or Europe (12 percent). Companies located in Taiwan, Korea, and Israel also produce carbon fiber. Capacity in the FSU has not been determined. Table 3.6 also indicates foreign ownership of capacity. Japanese companies, for example, own plants in Japan, the United States, and Europe accounting for 59 percent of global capacity. High strength and high stiffness fibers for demanding applications (including military) may account for 25 percent of global PAN-based capacity.⁷ Table 3.6 reports an estimate of 14.5 million pounds as the 1993 demand for PAN-based carbon fiber. This constitutes only 56 percent of global capacity. Because consumption requirements

⁷ This is a rough estimate based on a presentation at the National Materials Advisory Board workshop, August 1994.

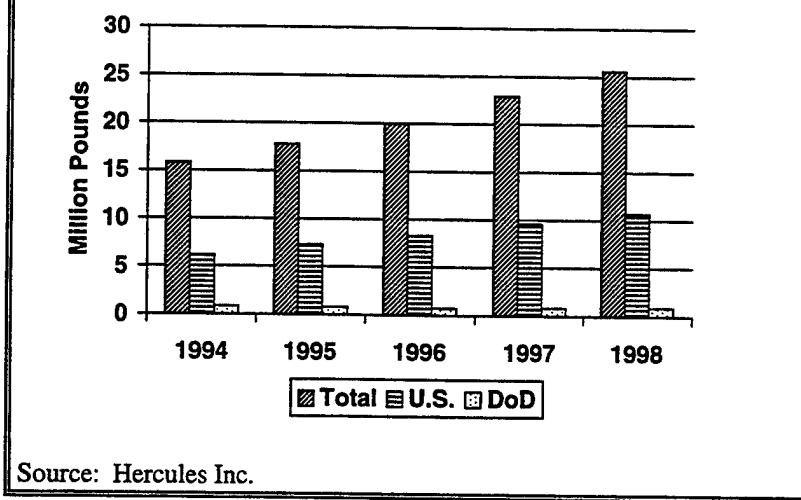
are satisfied by both domestic production and imports, these data cannot be used to determine capacity utilization for particular regions.

For pitch-based carbon fiber, global capacity is 4.1 million pounds per year, as shown on Table 3.7. Almost 89 percent of that capacity is located in Japan.

Table 3.7 - Pitch-Based Carbon Fiber Capacity (1992)			
Company (Owner)	Location	Ownership	Capacity
Amoco	US	US	0.46
Kureha Chemical	Japan	Japan	1.80
DONAC	Japan	Japan	0.60
Mitsubishi Kasei	Japan	Japan	1.00
Nippon Oil	Japan	Japan	0.10
Nippon Steel	Japan	Japan	0.10
Tonen (25% Mobil/25% Exxon)	Japan	Japan/US	0.02
Petoca	Japan	Japan	0.02
Japan Subtotal			3.65
GRAND TOTAL			4.11
NOTE: Table based on August 1992 Toray data reported in Wilkins, et al., April 1994.			

DoD consumption of PAN is significantly below the expectations held several years ago. According to both the Suppliers of Advanced Composite Materials Association (SACMA) and the United States Advanced Ceramics Association (USACA), a forecast made in 1987 projected DoD carbon fiber usage to be 4.8 and 6.1 million pounds for 1991 and 1992. Actual consumption was 1.0 and 1.1 million pounds respectively. It was feared that the decline in DoD procurement would lead to a massive decline in the industry. That decline has not materialized. Global consumption of PAN based fiber (all grades) has been increasing as indicated on Figure 3.2. Both global and U.S. consumption are projected to increase at a similar rate as depicted in Figure 3.2. Figure 3.2 also shows that defense applications (primarily aerospace grade fiber) account for a shrinking percent (less than five percent) of the market.

Figure 3.2 - World PAN Market



Japan's Toray Industries, Inc. is reputed to be the "recognized world leader in carbon fiber."⁸ It is a vertically integrated company, making precursors and fibers as well as high speed production equipment, woven forms, resins, preregs, and components. Toray has highly automated plants making the widest available range of PAN-based carbon fibers, with different combinations of tensile strength and modulus. Toray has a joint venture to produce carbon fiber in France with Elf-Aquitaine (to supply Airbus), and also owns Composites Horizons, a California maker of composites. Toray is thought to realize certain economies of scale through bulk purchasing and other commonalities between its textile and carbon fiber plants in Japan.⁹

Toray gained a significant share in the U.S. market by winning a contract to supply carbon fiber for the tail and floor beams of the new Boeing 777 commercial airliner. Toray built a 4.5-million-square-foot plant near Seattle to supply carbon fiber/epoxy prepreg to Boeing, utilizing T800H carbon fiber produced in Japan.¹⁰ Since Toray fiber and resin materials are now qualified, and as Boeing gains confidence in the materials over time, it will be very difficult for U.S. companies to break into this market. Consequently, Toray has the inside track to Boeing and to other U.S. manufacturers who choose to rely on Boeing's material specifications. This will also reinforce Toray's existing credibility as a supplier to Airbus.

The dominant producers within the United States, Amoco and Hercules, are both large companies for whom carbon fiber production is only a minor business. In the nine months ending September 1994, Amoco had a net income of \$1.3 billion on sales of \$19.2 billion;

⁸ Dick J. Wilkins et al., "Advanced Manufacturing for Polymer Composite Structures in Japan," Japanese Technology Evaluation Center (JTEC), April 1994, p.78.

⁹ Franklin Carvalho, U.S. Commerce Department report *Foreign Industry Analysis - Advanced Composites*, May 1993, pp. 15,28,34.

¹⁰ See Wilkins et al., April 1994, p. 160.

Hercules earned \$183 million on sales of \$2.1 billion.¹¹ Both have the financial muscle to compete with the large Japanese producers. However, unless there is a prospect of profitable and substantial growth in the market for carbon fiber (and composites), corporate management in both companies may limit further investment in R&D and market development or withdraw from the market entirely.¹²

The government intervened to support domestic production of PAN in the 1980s. The United States imported a substantial share of its PAN precursor from Japan in 1984, reportedly because imports were cheaper.¹³ Difficulties were also reported in obtaining the acrylic precursor to the PAN fiber from domestic suppliers uninterested in the small volumes involved. In 1988 and 1989 Congress mandated that 50 percent of the carbon fiber used for defense be made from domestic PAN precursor.

When the Congressional requirement was established, Amoco was the only producer using U.S. made PAN precursor, but could supply only 15 percent of the market.¹⁴ Thereafter, plans to expand or build new PAN precursor plants were announced by Amoco, Hercules, Courtaulds, and BASF. While the United States still imports PAN precursor, there are now domestic sources at Amoco and Hercules. Hercules produces its PAN precursor fiber at the HISPAN Corporation in Decatur, Alabama. In addition, Japanese companies retain a strong position as PAN suppliers to their subsidiaries in Europe and the United States.

The competitive standing of the U.S. industry is difficult to pin down because there is very little trade data available for carbon fibers.¹⁵ A Commerce Department survey of U.S. producers indicated that exports of carbon fiber accounted for 9.4 percent of shipments in 1989 and 13.5 percent in 1991.¹⁶ Some respondents to the same survey imported carbon fiber from Japan, citing better quality and lower price.¹⁷ Substantial Japanese exports can be inferred from the data on Table 3.6.¹⁸ In 1993 there were reports that U.S. carbon fiber prices were above the world market price, in part due to Congressional efforts to support domestic PAN capacity.¹⁹ The 1994 increase in the dollar value of the yen makes U.S. prices more competitive.

¹¹ See the 10-Q forms filed with the Securities and Exchange Commission.

¹² For example, a 1993 article in *New Technology Week* commented that Amoco planned to sell its composites division. See Crawford, June 14, 1993, p. 7.. Note that neither Amoco nor Hercules sold their carbon fiber business.

¹³ "Critical Technology Assessment of the U.S. Advanced Composite Industry," U.S. Department of Commerce, December 1993, p. 116.

¹⁴ See National Center for Advanced Technology, September 1991, p. 91.

¹⁵ Carbon fiber is not defined as a distinct product in the harmonic system for trade classification used by the United States, even at the 10-digit level.

¹⁶ See U.S. Commerce Department, December 1993, p. 67.

¹⁷ See U.S. Commerce Department, December 1993, p. 120.

¹⁸ For example, consumption represents 47 percent of capacity in the United States, 29 percent in Japan, 103 percent in Europe, and 303 percent in other areas. If there were no trade, these numbers would indicate a much lower capacity utilization rate for Japan than for the United States. If instead we assume that each region had the same utilization rate (56 percent), then it is apparent that the United States and Japan exported fiber (1.1 and 2.7 million pounds, respectively) while Europe and other areas imported it.

¹⁹ See Carvalho, May 1993, p. 17.

In summary, the DoD demand for carbon fibers is now below a million pounds per year, less than five percent of the global market. There also is excess capacity in the carbon fiber industry. While there have been some fears that the DoD decline would be catastrophic to the industry, non-aerospace and commercial applications are projected to increase (by as much as 14 percent annually according to some analysts) over the next five years and are expected to sustain the industrial base.

There is one item of special interest. DoD's Theater High Altitude Area Defense (THAAD) Program has a requirement for high modulus (greater than 50 million pounds per square inch), high strength (greater than 500,000 pounds per square inch) PAN carbon fiber. Currently, Toray Industries is the only company with a product (M40J) to meet these needs and therefore DoD will remain dependent on Toray through the early part of the next decade. While access to M40J is not absolutely guaranteed, there are however no indications that Toray Industries will not continue to produce and sell M40J. Theoretically, if this situation were to change, Amoco or Hercules could develop an alternative. In fact, Hercules has stated informally that it has the technology to make an equivalent fiber.

Other Reinforcement Fibers

DuPont Company (Wilmington, DE) is the sole U.S. producer of Kevlar aramid (aromatic polyamide) reinforcement fiber which is used in advanced composites. Aramid fiber is used in a variety of aerospace applications including filament-wound pressure vessels and aircraft control surfaces, but has been largely replaced by carbon fibers in many structural applications.

Owens-Corning Fiberglas (Toledo, OH) is the sole U.S. producer of S-2 high strength fiberglass reinforcement (\$5 per pound). It has higher strength than E-glass (\$2 per pound) and is more expensive, but is used in some high performance composite applications. For example, S-2 fiberglass is used in pressure vessels, fuel pods, radomes, rotor blades and ballistic armor.

Textron Specialty Materials (Lowell, MA) is the sole U.S. producer of high strength, high stiffness boron fibers which have been used in advanced composites. First military use of these fibers was on the F-14 Tomcat in the 1970s. The annual consumption of these fibers is very low (less than 50,000 pounds) due to their high cost and current low demand for these reinforcement fibers. Boron fibers cost about \$850 per pound; boron/epoxy prepreg sells for approximately \$550 per pound.

In comparison with carbon fibers, other reinforcements comprise a very small portion of the fiber reinforcement industry for advanced polymer composites. Exact figures for the annual production of these fibers are proprietary and are not given here. There appear to be sufficient niche markets and applications for these materials for their industrial base to remain viable in the future.

3.1.3.3 Prepreg Suppliers

The prepregger is analogous to the compounder in the plastics industry as to position in the chain of supply, that is, midway between the resin and fiber suppliers and the fabricators. Basically, the prepregger combines a resin (e.g., an epoxy resin) and a fiber (e.g., carbon fiber) into a usable intermediate product (e.g., carbon/epoxy prepreg) which is the material used by a fabricator to make composite parts and structures.

There are a variety of materials and curing agents to choose from, and prepregging is highly proprietary. The prepregger must achieve the proper balance of shelf life, compatibility with the fabricator's process, convenience in handling, and correct properties for the finished part. For these reasons, prepreggers were originally independent entities. However, restructuring in the industry has occurred and few independent prepreggers remain today.²⁰ Some resin and fiber suppliers have in-house prepregging capabilities.

Major prepreggers (with major product) are listed below:

U.S.
Cytac Industries (5250-4 BMI)
DuPont (K-polymer)
Quadrax (8320 thermoplastic)
Hercules (3501-6 epoxy)
Hexcel
FiberCote Industries

non-U.S.
Toray Industries Inc.
Ciba Composites (MY720)
ICI Fiberite (977-3 epoxy)
Mitsubishi Rayon Company, Ltd.
Nippon Graphite Fiber Corporation

As shown above, there are numerous U.S. and non-U.S. sources of prepreg composite materials in the commercial marketplace. Many of the prepreg companies are owned by large firms, and consequently represent only a small portion of the overall business base. As a consequence, financial backing for the prepreg companies could be made available if corporate management chooses to do so. Most U.S. prepreg companies have qualified materials for military applications (e.g., Hercules' 3501-6, Cytac's 5250-4), and consequently current DoD programs will provide some sustainment of the industrial base.

3.1.3.4 Fabricators

There are numerous fabricators who make advanced composite parts. Some examples include: Composite Horizons, Kaiser Compositek, Hercules (filament-wound Titan IV Solid Rocket Motor Upgrades), DuPont, and Dow/United Technologies (F-22 resin transfer molded

²⁰ According to SAMPE Journal, Vol. 31, No. 5, September/October 1995, Hexcel and Ciba have jointly announced that a letter of intent has been signed by which Ciba's Composite Division will become a part of Hexcel by the end of the fourth quarter of 1995. In return, Ciba will receive 49.9 percent of Hexcel's stock.

parts). The subtier parts manufacturers and subcontractors also have broad industrial capabilities in composites manufacturing processes which are more than adequate to meet current demands.

Aerospace prime contractors are the assemblers and integrators of systems which use advanced polymer composites. The list of U.S. primes which have industrial capabilities for composites fabrication includes Boeing (Seattle, Wichita, Philadelphia), Northrop Grumman (Hawthorne, El Segundo, Pico Rivera, Bethpage, Stuart, Vought/Ft. Worth), Lockheed Martin (Marietta, Ft. Worth), Bell-Helicopter (Ft. Worth), McDonnell Douglas (St. Louis & Tempe), and Sikorsky (Bridgeport). Typically, these fabricators employ autoclave curing of thermoset epoxy composites to produce composite structures. There is excess fabrication capacity for advanced polymer composites at U.S. prime contractor facilities. Each prime contractor has multiple autoclaves and the industrial capabilities for composites fabrication exceed DoD requirements. Other composite manufacturing processes (most of which are subcontracted out by primes) include filament winding, injection and compression molding, pultrusion, resin transfer molding, stamping and thermoforming.

Table 3.8 describes 1992 production by region and indicates that the United States produced about 55 percent of the world total.

Table 3.8 - 1992 World Production of Advanced Composites by Region		
Region	Quantity (thousand metric tons)	Value (million dollars)
Pacific Rim	2.7	817
North America	7.5	2,236
Western Europe	3.4	1,247
Worldwide	13.7	4,300
Source: Kline & Co., Inc.		

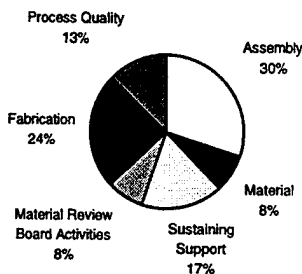
The primary problem confronting high performance PMCs at this time is cost. Components fabricated from the aerospace quality materials needed for most defense applications are expensive. In separate studies, the U.S. Air Force and McDonnell Douglas Aircraft Company found that finished composite parts for use on military aircraft cost from \$300 to \$500 per pound²¹ (comparable aluminum parts cost about \$200 per pound) but that actual materials costs for fiber and resin comprised only 8 to 10 percent of that cost (see Figure 3.3). Ninety percent of the cost of finished parts was due to processing, fabrication, assembly, quality

²¹ Ranges from \$100 to \$1,500 per pound have been reported.

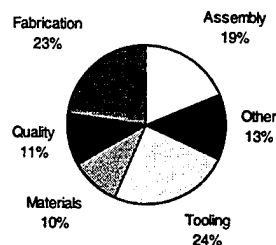
control and materials review board actions, all done by the component fabricators, usually aircraft primes such as McDonnell Douglas, Northrop, and Boeing.

Figure 3.3 - Reduced Manufacturing Cost is Key to Affordable Composite Structures

Recurring Costs From McDonnell Aircraft Company
Summary F/A-18, AV-8B, A-12, F-15, YF-23 Data



"Direct Cost Elements in Manufacturing of Polymer Matrix Composites," Final Draft Airforce Materials Processing and Fabrication Strategic Plan



Source: U.S. Air Force and McDonnell Douglas Aircraft Company

3.1.4 PMC Government Programs

R&D, Manufacturing Technology, and Title III

U.S. Government support, primarily from DoD and NASA, for research and development efforts including technology demonstrations and manufacturing technology programs provided the technology and the technical know-how that, combined with the hardware development efforts of the aerospace industry, have created the current advanced composites industrial base. Those efforts focused on performance with only limited concern for cost. Now the focus has been shifted to cost, with two particular thrusts. Both the Advanced Research Project Agency (ARPA) Technology Reinvestment Program and the National Institute of Standards and Technology (NIST) Advanced Technology Program have projects focused on dramatic reductions in processing costs and application of the resultant less expensive materials to a variety of non-aerospace uses, including commercial infrastructure. The primary goal of the ARPA and NIST efforts is to achieve further cost reductions by greatly expanding the markets for the basic materials and the procedures for processing them. The projected benefit to DoD would be a healthy, high performance composites industry that could then provide advanced composites for military markets at lower than current costs.

The U.S. Government has had a substantial impact on the development of the carbon fiber industry, especially through steady funding of R&D for several decades. The government was also a pioneer customer for carbon fiber composites -- DoD usage still accounts for about 25 percent of domestic carbon fiber consumption. Two recent projects involve the development of specialized types of pitch-based carbon fiber.

The Navy is currently funding a Manufacturing Technology project to develop a pitch-based carbon fiber with high thermal conductivity (more than 1000 Watts/meter-Kelvin).²² The fiber will be used in polymer or metal matrices to dissipate heat, particularly for electronics applications. Clemson University and Amoco will develop and commercialize the fiber. A major goal is to reduce fiber cost below the current \$1000 per pound.

The Navy's Center of Excellence for Composites Manufacturing Technology, operated by the Great Lakes Composites Consortium (GLCC), is a program which is fostering development of advanced manufacturing processes for the production of affordable and reliable weapon systems. Navy funding has been about \$60 million over the last five years. Under this program, GLCC developed Advanced Fiber Placement (AFP), an automated, repeatable process for reducing labor, material and manufacturing costs, and ultimately, lower fabrication costs. This development resulted in AFP being baselined as the manufacturing process for the fabrication of horizontal stabilator skins and engine inlet ducts on the F/A-18E/F aircraft. During 1994, the critical specifications developed under the AFP program were transferred to Boeing Helicopter and Bell Helicopter for use on the V-22. The GLCC is also demonstrating resin transfer molding (RTM) as a cost effective and reproducible manufacturing process for fabrication of lightweight polymer composite structures.

In 1988, DoD initiated a Title III (of the Defense Production Act) program to establish a secure, consistent, production level domestic capacity of high modulus pitch-based graphite fiber. The \$7.9 million, five year contract was with Amoco Performance Products. Initial production runs resulted in a material which had superior thermal, but unacceptable structural characteristics. Responding to this situation, as well as to the dynamics of the market place (competitor and customer movements), the Title III Program Office restructured the contract to take advantage of a Navy manufacturing technology program and to improve the material attributes. The improved material answered customers needs, and the infused technology has migrated throughout the contractor's entire product line.

Although the contract ended in 1994, Amoco continues to produce a world class product, and is successfully selling the material (and derivatives) to military customers as well as to the commercial market. This project resulted in the creation of a strong, viable domestic production capacity (10,000 pounds per year), competitively reduced prices, and new domestic employment opportunities. The material, which is substituted for traditional steel and aluminum, provides increased stiffness, reduced weight, improved thermal characteristics, and greater corrosion and fatigue resistance. Major applications include military and commercial satellites, the space station, and the Boeing 777 engine cowlings.

²² See Manufacturing Technology Program Summaries 1992-3, p. 144, also discussed in Section 3.4 of this chapter.

Major Acquisition Programs

Even with the end of the Cold War and the major reductions in DoD procurements which have occurred as a result, there are still several major DoD acquisition programs which will help to sustain the advanced polymer composites industrial base. The F-22 air superiority fighter will be comprised of about 25 percent (by weight) advanced polymer composites, including materials supplied by Cytec (5250-4 BMI) and ICI Fiberite (977-3 epoxy). The current planned buy is for 442 F-22 aircraft. The Navy's F/A-18E/F will be constructed of about 20 percent (by weight) advanced polymer composites and also uses ICI's 977-3 toughened epoxy prepreg. The Navy plans to buy 1,000 of the F/A-18E/F aircraft. The C-17 transport aircraft currently in production uses substantial quantities of composite materials. The Titan IV Solid Rocket Motor Upgrade is a large (10 feet diameter) filament-wound composite structure which uses Hercules IM7 carbon fiber. The Trident D-5 missile uses Hercules IM carbon fiber in all three stages. Other future potential production programs which would use large amounts of composite materials are the V-22 tilt rotor aircraft, the RAH-66 helicopter, and various missiles and rockets. In conjunction with R&D, DoD's aircraft and missile applications will continue to sustain the advanced polymer composites industrial base, although at a much reduced level than was predicted in the late 1980s.

3.1.5 PMC Assessment

There has been significant recent restructuring in the advanced PMC industry due to downturns in the military aerospace markets, reflected by plant closings and declining sales in the past few years. This assessment was undertaken to evaluate the effect of this restructuring on affordable, assured military access to advanced polymer composites technology.

The approach taken in this assessment was to examine the advanced PMC industry in four parts -- the matrix resin industry, the reinforcement fiber industry, prepreg suppliers, and fabricators. Findings in each of these areas are discussed in the following four paragraphs.

The matrix resin industry for advanced polymer composites is a spin-off of the much larger plastics industry. The resin suppliers for advanced polymer composites are generally large chemical companies involved in high volume plastics production for which specialty resins are only a small portion of their overall business base. As a consequence, the industrial base for advanced polymer resins (thermosets or thermoplastics) is well established and there are no significant concerns that industrial capabilities necessary to meet future military requirements will be lost.

DoD demand for carbon fibers is now below a million pounds per year, less than five percent of the global market. There also is excess capacity in the carbon fiber industry. While there have been some fears that the DoD decline would be catastrophic to the industry,

non-aerospace and commercial applications are projected to increase over the next five years and are expected to sustain the industrial base. The only potential question relates to domestic suppliers of PAN precursor. A question has been raised concerning the need for continuing the restriction that 50 percent of the carbon fiber used in defense systems be made from domestic PAN precursor. This policy issue is being addressed separately from this assessment. In comparison with carbon fibers, other reinforcements comprise a very small portion of the fiber reinforcement industry for advanced polymer composites. There appear to be sufficient niche markets and applications for these materials for their industrial base to remain viable in the future. Consequently, the industrial base to satisfy military requirements does not appear to be in jeopardy.

There are numerous U.S. and non-U.S. sources of prepreg composite materials in the commercial marketplace. Many of the prepreg companies are owned by large firms, and thus represent only a small portion of the overall business base. As a consequence, financial backing for the prepreg companies could be made available if corporate management chooses to do so. Most U.S. prepreg companies have qualified materials for military applications (e.g., Hercules' 3501-6, Cytac's 5250-4), and consequently current DoD programs will provide some sustainment of the industrial base. No immediate issues regarding DoD requirements are foreseen.

There is excess fabrication capacity for advanced polymer composites at U.S. prime contractor facilities. Each prime contractor has multiple autoclaves and the industrial capabilities for composites fabrication exceed DoD requirements. The subtier parts manufacturers and subcontractors also have broad industrial capabilities in composites manufacturing processes which are more than adequate to meet current demands. Therefore, while additional rationalization will inevitably occur, assured affordable access does not appear to be an issue. The primary problem confronting high performance PMCs at this time is cost. However, based on the government programs underway, affordability issues associated with material production volume and component fabrication for military and commercial markets are being adequately addressed.

In conclusion, the PMC industry has downsized to a capacity consistent with demand and there does not appear to be any danger of losing assured access to polymer composite technology. It should, however, be noted that nothing in this assessment precludes DoD from funding PMC insertion efforts. In fact, such efforts should be favorably considered if cost savings to DoD can be quantitatively demonstrated.

3.2 Ceramic Matrix Composites (CMCs)

3.2.1 CMC Overview

CMCs provide significantly higher strain-to-failure and significantly higher fracture toughness than do monolithic ceramics. These attributes reduce the principal limitations that have heretofore limited the use of ceramics in highly stressed structural applications.

In the mid 1980s, the U.S. advanced ceramic industry was anticipating extremely rapid growth. Ceramic engines were thought to be a near term demand driver. The industry also assumed that DoD would become a major purchaser of CMC armor. These, and other potential new markets have not materialized. In fact, outside of electronic ceramics (a \$4 billion market), the advanced ceramic industrial base is small, and in some cases, embryonic. Therefore, this study was undertaken to identify potential issues of assured, affordable access to CMCs, particularly for structural ceramics products.

Two major classes of ceramic matrix composites exist: discontinuously reinforced and continuously reinforced CMCs. Discontinuously reinforced CMCs (also known as second phase toughened ceramics) consist of a matrix phase (frequently, aluminum oxide or silicon nitride) to which a reinforcing phase (for example, silicon carbide particles, platelets or whiskers) is added. Discontinuously reinforced CMCs are presently in the early stage of commercialization (e.g., aluminum oxide/silicon carbide whisker cutting tools). They are principally utilized in applications where wear is a major issue. Some typical applications and materials (matrix/reinforcement) are listed below:

<u>APPLICATION</u>	<u>MATERIAL</u>
• Cutting tools	Alumina/Silicon carbide-whisker, Silicon nitride/Silicon nitride
• Canning dies	Alumina/Silicon carbide-whisker
• Extrusion dies	Silicon nitride/Titanium nitride- particulate
• Wear parts (e.g., valve guide)	Silicon nitride/Chopped carbon fiber
• Armor	AlN/25 percent SiC-particulates
• Radomes	Silicon nitride/Oxides

Continuous fiber reinforced CMCs consist of an array of continuous ceramic fibers, either uniaxially arrayed, multi-axially arrayed, or woven as a cloth, that are embedded in a ceramic or glass matrix. Continuous fiber reinforced CMCs are currently at the pre-commercial development/application demonstration stage. Continuously reinforced CMCs are principally being developed for utilization in applications where high temperature, thermal shock, and or steep temperature gradients are superimposed with high stresses. Some typical applications and materials (matrix/reinforcement) are listed below:

APPLICATION

- Gas turbine combustors
- High Pressure heat exchangers
- Hot gas filters
- Gas Turbine nozzles and seals

MATERIAL

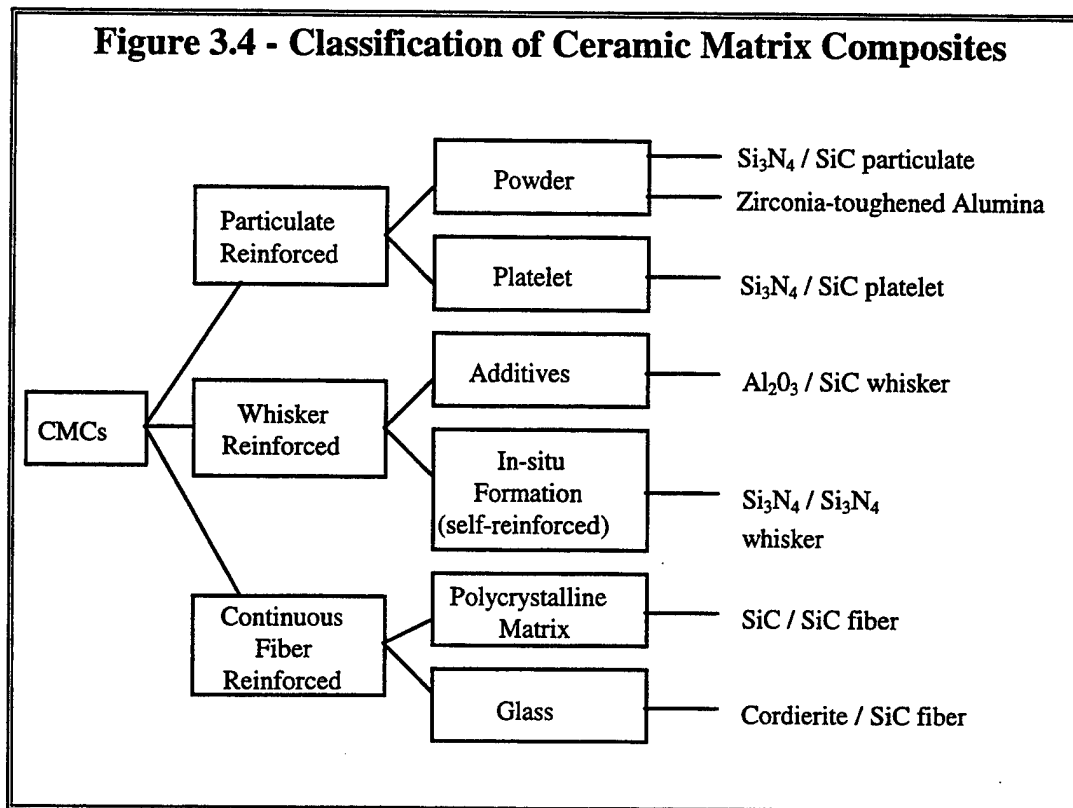
Silicon carbide/Silicon carbide
Alumina/Alumina

Silicon carbide/Silicon carbide
Alumina/Alumina
Zirconia/Alumina

Alumina/Alumina
Silicon carbide/Silicon carbide

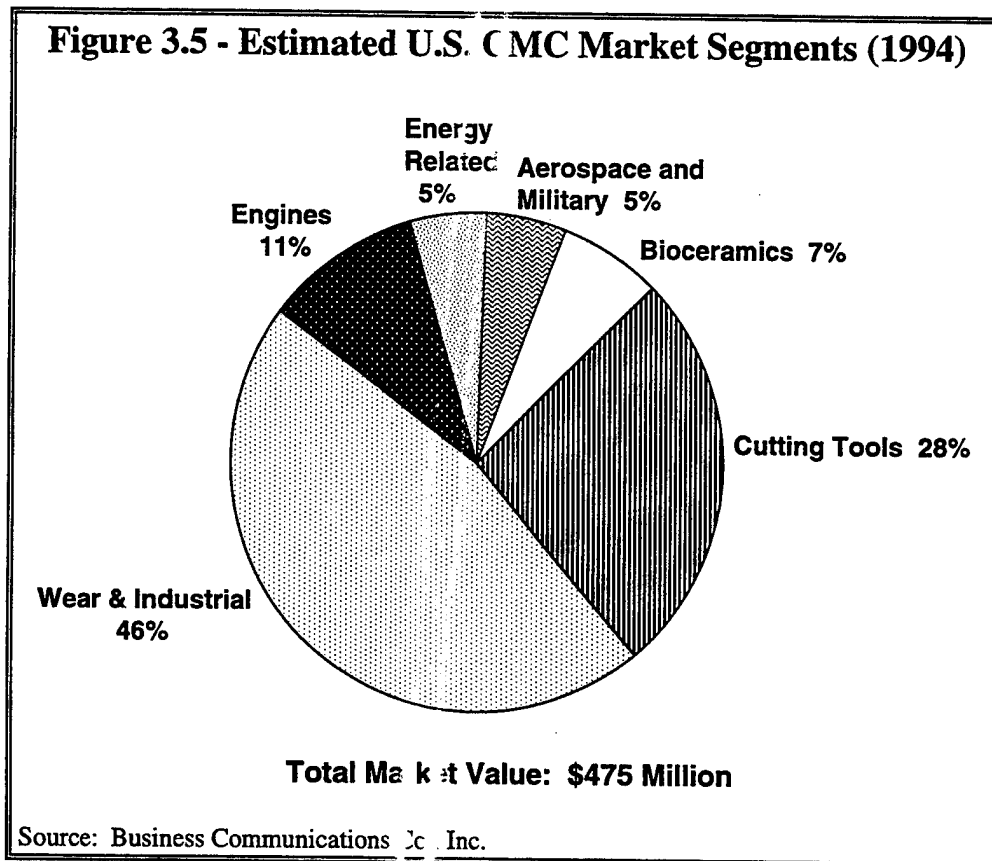
Blackglas/Alumina,
Silicon carbide/Silicon carbide

Figure 3.4 presents a systematic overview of the existing categories of CMCs.



3.2.2 CMC Demand

A generalized estimate of 1994 U.S. market volume in CMCs has been published by Business Communications Company, Inc. (BCC), as reproduced in Figure 3.5. It shows a total 1994 market of \$475 million, up from approximately \$115 million in 1992. BCC also projects a 13.5 percent annual growth rate through the year 2000 where the total market size may reach \$1 billion. While no distinction is made between fiber-reinforced and discontinuously reinforced composites in this estimate, a vast majority of the \$475 million falls in the latter category.



A key commercial consideration for this technology is its potential to mitigate environmental problems in both aircraft and ground power systems and high temperature industrial processes in general. Industries that must increase control over emissions, fuel consumption or other consequences tied to operational temperatures have identified CMCs as necessary replacement structures for use in their processes. Airlines looking for increased cruising speeds and more efficient fuel consumption must also comply with ever more stringent noise and high altitude emissions regulations. Throughout the high temperature process industries (e.g., chemical industry, incineration industry, etc.), the need also exists for materials/structures with sufficient reliability to minimize system shutdown and maintenance times, as well as preventing catastrophic structural failures.

Department of Energy (DoE) CMC demonstration programs have provided estimates of the size of the future commercial market. The estimates shown in Table 3.9 reflect a scenario in which CMCs have achieved a 20 percent market share in each of the application areas.

Table 3.9 - Potential DoE Markets for CMCs	
Application	Annual Market Potential (in millions)
Clean Burning Gas Turbines for Power Generation	\$150-200/year
High Pressure Heat Exchange Systems	\$150-300/year
Efficient Waste Incineration Components	\$500/year
High Temperature Radioactive Burners	\$60/year
Hot Gas Cleaning	\$110/year
High Efficiency Reformer Components	\$15/year
Cutting Tools and Wear Parts	\$100/year
TOTALS	\$1,085-1,285/Year
Source: Overview of Continuous Fiber Ceramic Composites Program, DoE, October 18, 1994; separate estimate by R.N. Katz, Army Research Lab, for cutting tools and wear parts.	

For defense applications, CMCs can enhance the survivability and significantly increase the operating efficiency of many high temperature military systems. In particular, the use of continuous fiber CMCs to reduce the signature of military aircraft engines and engine related structures is a critical technology required to assure high survivability aircraft for future combat and operations-other-than-war missions. Additionally, jet engines utilizing CMC components that will be lighter than those made from competing materials, and that can operate with higher temperatures without cooling, will pay large dividends in increased propulsion efficiency, leading to greater payload carrying ability, greater range, higher performance. These benefits would apply to both military and civilian aircraft, given that other requirements in costs, reliability and serviceability can be met by the new materials. In addition, discontinuous CMCs are needed to meet future DoD armor requirements.

In some cases this enhanced military performance can be coupled with major cost reductions or avoidance. One example, provided by General Electric Company at a recent ARPA Ceramic Insertion Program Review, is presented in Table 3.10.

Table 3.10 - Life Cycle Cost Savings Estimated for CMC Replacement Parts	
CMC Flaps & Seals for F110 Engine Family	
Component	Life Cycle Cost Savings
Divergent Flap	\$4,355,449
Divergent Seal	\$4,174,352
Total	\$8,529,801
Based on a total fleet of 858 engines Total of 325,968 engine/hours for the fleet Data from GE, presented at 1993 ARPA Ceramic Program Review	

Another example of a recent successful application of discontinuous CMCs for a DoD application occurred during the Gulf War. ARPA responded to a requirement to upgrade the protection level on the Marine's light armored vehicles by providing applique tiles of Al_2O_3/SiC particulate. Twenty thousand of these tiles were fabricated and delivered in less than two months. The contractor was able to successfully increase the production rate almost 40-fold, and achieve a production cost of about \$7 to \$8 per pound.²³

Often commercial products can satisfy military needs. An example of a dual use application of continuously reinforced CMCs is the development of an interstage seal for the Allison AE 3007 Turbofan Engine. This Blackglas-Nextel-312 continuously reinforced CMC is being developed under ARPA sponsorship in a materials partnership program conducted by the Low Cost Ceramic Composites Virtual Company. This component is expected to provide a 74 percent weight savings per component.

In summary, while there are significant possibilities for DoD demand, the potential demand for discontinuous CMCs far outweighs the potential demand for continuous CMCs. The higher structural stability and operating temperature capability of continuous CMCs do not justify the additional costs except in a few specific (principally turbine engine) applications where these properties provide a discernible military advantage over discontinuous CMCs. Within the government, DoE has a far greater demand potential for continuous CMCs than does DoD.

²³ C. R. Kennedy, Lanxide Corporation, in *Proceedings of the Advanced Materials and Processing Technology Workshops*, (CIAC/MIAC/HTMIAC Special Report), August 1991.

3.2.3 CMC Industry Structure

Ceramic powders, used to form CMC matrices²⁴, are common to both the discontinuously reinforced and the continuous fiber industries. In some cases, these are the same types of powder used to manufacture monolithic structural ceramics. However, high performance CMC and ceramic components (often needed by DoD) generally require specialized powders, with very high purity and highly uniform grain size and shape. In addition, powders for CMCs must be compatible with the reinforcement material. Particular applications may also demand powders that yield tailored properties. However, because these specialized powders are related to the powders needed for the much larger market for monolithic structural ceramics primarily for electronic packaging, a solid U.S. base (along with France and Japan) for specialized powders is expected to emerge as demand grows. Therefore, while DoD may drive requirements for specialized powders in some demanding cases, it will nevertheless benefit from a large, commercially oriented, globally integrated production base.²⁵

Beyond ceramic powders, the structure of the CMC industry differs for discontinuously reinforced and continuously reinforced composites. For the discontinuously reinforced CMC segment of the industry the manufacturing base largely exists. It consists of:

- Producers of reinforcements (particles, platelets and whiskers)
- Producers of consolidated CMC components or billets.

By contrast, the continuously reinforced CMC industrial base is in the process of formation. This nascent industrial base consists of:

- Producers of ceramic fibers (about 10 to 20 microns diameter) or monofilaments (about 100 or more microns diameter)
- Interface designers/fiber modifiers
- Textile preformers (weavers, braiders, winders, etc.)
- Composite fabricator (integrates fibrous preforms and matrix into finished parts)

Table 3.11 shows representative companies, laboratories and other organizations that have been active in some or all aspects of CMC technologies. As such, it is not meant to be an exhaustive listing, but does show some of the participants in current CMC programs, initiatives, and product lines. Because of the relatively immature nature of the CMC industry, lines have not been used to illustrate relationships between organizations. In addition, the divisions between sectors are not definitive; some companies are more vertically integrated than others in CMC

²⁴ A common method is to infiltrate a reinforcement with a powder slurry and consolidate via high heat and/or pressure. Other methods use gaseous or polymeric precursors rather than powders.

²⁵ The defense share of U.S. advanced ceramics shipments was only 4.6 percent in 1990 and 1.5 percent in 1993 in the industry sample reported in the Commerce Department's, *Critical Technology Assessment of the U.S. Advanced Ceramics Industry*, p. iii.

technology (e.g., some fiber manufacturers or CMC component fabricators may also weave their own reinforcement fabrics, or put on interface coatings). Hence, the industry infrastructure for CMCs can still be considered to be in an earlier stage of evolution, when compared with PMCs.

Table 3.11 - CMC Industry Structure

<i>Constituent Materials</i>	<i>Intermediate Processors</i>	<i>Component Fabricators</i>
Silicon Carbide Fibers Dow Corning Nicalon* (Dow Corning) Tyranno* (Textron)	Fiber weavers Fiber Materials Inc. Techniweave 3M	SiC/SiC Allied-Signal Amercom DuPont/Lanxide Composites GE Aircraft Engines Kaiser Aerotech Pratt & Whitney Textron Specialty Materials
SiC Monofilaments Amercom SCS Series (Textron)		
Alumina-based Fibers Almax* Altex* (Textron) Saphikon 3M Nextel (400s, 550, 610)	Fiber Coaters Amercom BIRL Corning Inc. Synterials 3M	Alumina/Alumina Babcock & Wilcox GEAE 3M
Matrix Materials Alcoa Allied-Signal ART Carborundum Dow Corning		SiC/Si₃N₄ Dow Chemical NASA-Lewis

* Non-US Sourced

Discontinuously reinforced CMCs are an extension of high performance monolithic ceramics technology and consequently the industrial base for these materials is an extension of the existing monolithic ceramics industry. While improvements and optimization of any specific material, reinforcement, or process are continually being pursued, the following general observations presently characterize the discontinuously reinforced CMC industry and its products:

- Starting materials are similar to those used by the monolithic ceramic industry
- Shape forming processes (i.e., cold pressing, injection molding, etc.) and consolidation methods (i.e., sintering, hot pressing, etc.) are similar to those used by the monolithic ceramics industry
- Fully dense, well-bonded components are produced
- The mechanical and physical properties of the final material are usually isotropic
- Toughness (energy absorbed prior to failure) is increased, typically 25 to 100 percent
- Costs are only slightly increased over monolithic ceramics.

By contrast, continuous fiber CMCs are not an extension of the existing technology of the monolithic ceramics industry. Continuous fiber CMCs are not merely a materials system consisting of a matrix and a reinforcement, rather they are a material system with a superimposed, application specific reinforcement architecture. A specific material system/reinforcement architecture is custom designed to fit one specific use (or a limited set of uses). The fiber architectures may vary from simple uniaxial arrays to complex weaves and braidings. The key point is that the material and the structure are not separable entities. As a consequence the observations which characterize the continuous fiber CMC industry are very different than those that were presented above to characterize the discontinuously reinforced CMC industry and its product. These observations are:

- Starting materials may be very different than those used in the monolithic ceramics industry
- Shape forming processes are very different than those used in the existing monolithic ceramics industry
- Fiber matrix interfaces must be specifically designed and processed to accommodate high strain to failure
- Resultant products exhibit highly anisotropic mechanical and physical properties
- Resultant products exhibit high strength (in the directions of reinforcement) and high strain to failure (toughness)
- Costs are much higher than monolithic ceramics or discontinuously reinforced ceramics.

The remainder of this section focuses on the continuous fiber CMC industry, and in particular, the continuous fiber producers as opposed to continuous fiber CMC fabricators. There are several reasons for this focus.

- As an extension of high performance monolithic ceramics technology, the industrial base for discontinuously reinforced CMCs is relatively mature.
- There are many companies involved in the fabrication of continuously reinforced composites, as shown in Table 3.11. Several of these companies (e.g., DuPont, General Electric, Pratt & Whitney, Allied Signal) are relatively large and financially stable. They can afford to develop niche markets if they believe that there are profits to be made.
- The industry standard materials for continuous fiber producers are manufactured off-shore. Japan has positioned itself as the world leader in production of high performance fiber, providing an option to become a formidable competitor in the continuous CMC arena. The French have elected to target the opportunities afforded by continuously reinforced ceramics. Indeed they lead the world in insertion of components in production engines for jet fighters.

Continuous Silicon Carbide Fibers

Continuous silicon carbide (SiC) fibers are used as reinforcements in both MMCs and CMCs. However, different types of composites require different types of fiber. For titanium matrix composites, SiC monofilaments with large diameters (100 to 150 microns) are typically used.²⁶ For CMCs, SiC fibers with small diameters (less than 20 microns) are preferred.²⁷ Large and small diameter SiC fibers are made by different companies using different production processes.

Two Japanese companies lead the world in the production of small diameter silicon carbide fibers.²⁸ For a decade, they have been the major suppliers of these fibers for R&D work in the United States and Europe. The multifilament yarns are spun from inorganic polymeric precursors, cured, and pyrolyzed to ceramic at temperatures ranging up to 2500°F. They have individual filament diameters of about 9 to 15 microns.

The Nippon Carbon Company, the world leader, produces a silicon carbide fiber called Nicalon. The fiber diameter is 14 to 15 microns. The production capacity for Nicalon is estimated to be 24,000 pounds per year. Nicalon prices vary depending on grade and quantity purchased, but can be as low as about \$300 per pound.²⁹ Dow-Corning distributes Nicalon in the U.S.

Ube Industries makes a titanosilicocarbon fiber called Tyranno. It has a diameter of 9 to 11 microns. Ube is a chemical engineering company, and also produces high quality silicon nitride ceramics and whiskers. Tyranno fiber is distributed in the U.S. by Textron.

The "standard" grades Nicalon and Tyranno have property and compatibility limitations as reinforcements for CMCs in high temperature applications. They cannot operate in oxidizing environments above 2200°F and they degrade during the processing typical of many CMCs. Stronger, higher temperature-capable fibers are needed to meet (1) the DoD and NASA requirements on the Integrated High Performance Turbine Engine Technology (IHPTET) program for future military aviation engines and (2) the performance, economical operation, aircraft noise and upper atmosphere emissions requirements of the future High Speed Civil Transport (HSCT).

²⁶ For MMCs, large diameter monofilaments can be spaced out without reducing the fiber-to-metal volume ratio, taking advantage of the energy absorbing ductility of the metal matrix. With CMCs, however, it is desirable to pack the fibers densely in order to bridge cracks that develop in the brittle ceramic matrix. See the discussion by R.J. Diefendorf in the *JTEC Panel Report on Advanced Composites in Japan*, March 1991, pp. 29-33. Another consideration is that the monofilaments stand up better to hot isostatic pressing to form MMCs.

²⁷ See the description of the ideal fiber for CMCs in the National Center for Advanced Technologies (NCAT) *National Advanced Composites Strategic Plan*, September 1991, p. 202. The use of small diameter fibers for low-temperature MMCs is also being explored. See NCAT, 1991, p. 122.

²⁸ See Diefendorf, pp. 13,35-7,65,78,82.

²⁹ See NCAT, 1991, p. 238.

Both Nippon Carbon and Ube are known to be developing versions of Nicalon and Tyranno with improved high temperature properties, mainly through the reduction of final fiber oxygen contents.³⁰ There is some question whether these programs will meet IHPTET and HSCT requirements. Also, if the requirements can be met, the fact that these oxygen-reduced fibers require additional processing (such as exposure of the polymers to electron beams during crosslinking steps), imply prices ranging from several times to more than an order of magnitude higher than those of the standard grade fibers.³¹

Several small diameter silicon carbide fiber types are being developed in the U.S. The NASA Lewis Research Center is sponsoring Dow Corning's development of a 10 micron fiber based on a polymeric precursor.³² Other organizations developing silicon carbide fibers include British Petroleum's Carborundum Company,³³ the University of Florida (with sponsorship from the IHPTET Fiber Consortium), the University of Michigan, and MER, Inc.

While U.S. organizations, such as those cited above, are doing development work on alternative fibers, there is no production base in the U.S. that approaches Japanese capabilities in this area. DoD has used the Japanese fibers for its own R&D work, taking advantage of existing commercial capabilities developed with foreign government support. The fiber development consortia associated with the IHPTET and HSCT programs are relying on U.S. companies and universities. Technical successes and scale-up feasibility of these U.S.-derived fibers may lead to the establishment of production capabilities in the United States.

Continuous Alumina-Based Fibers

Continuous alumina fiber is used as a reinforcement for both MMCs and CMCs. Single crystal (sapphire) fiber is quite strong though relatively expensive. Polycrystalline alumina fiber has good stiffness but higher density and generally less strength than the best silicon carbide fibers. Its price is about one tenth that of SiC monofilaments. Polycrystalline alumina-based fibers are readily available in commercial quantities, though many of the higher performance versions are still in developmental stages.

Two U.S. companies are involved.

- Minnesota Mining and Manufacturing Co. (3M) uses a sol gel process to make the Nextel family of fibers with diameters of 10 to 12 microns. Lower temperature grades of Nextel (the 400 numbered series) are alumina-silica based, with small amounts of boria. Nextel 610 is a high performance, nearly pure alumina fiber

³⁰ For the example of Nicalon, see M. Takeda et al., *Ceramic Engineering and Science Proceedings, Volume 14, #4 (July-August 1994)*, pp. 133-141.

³¹ M.A. Karnitz and R.A. Lowden, *A Survey of the Status of Ceramic Reinforcement Technology and its Relationship to CFCCs for Industrial Applications*, 1994.

³² See Diefendorf, pp. 36-7.

³³ As of this writing, the Saint-Gobain Company of France had tendered an offer to buy Carborundum.

that is now becoming scaled up to commercial production.³⁴ 3M is also developing another alumina-silica fiber (tentatively coded Nextel 720), reportedly with improved high temperature deformation resistance over Nextel 610.³⁵

- Saphikon, Inc. uses an extraction technique from molten alumina baths to produce a single crystal (sapphire) monofilament with diameters ranging up to about 150 microns. These fibers have greater tensile strengths at room temperature than polycrystalline fibers, but have been inherently expensive to produce. ARPA and General Electric have funded Saphikon to scale up their production capability and lower costs. NASA-Lewis has developed experimental sapphire fibers (with other oxides as additives) using a laser heated float zone (fiber drawing) process. Fiber diameters are about the same as the Saphikon materials.

In Japan, Sumitomo Chemical Company produces Altex, an alumina-silica polycrystalline fiber with 10 to 15 micron filament diameter, using an alkaline-oxide precursor. A current production rate of about 30,000 pounds per year has been estimated.³⁶ Textron distributes Altex in the U.S. Also in Japan, Mitsui Mining Company produces a high-alumina fiber with the trade name Almax. This product is similar to Nextel 610, but the latter has been acknowledged to have superior properties.³⁷

In summary, there is a U.S. presence in the continuous alumina-based fiber market. Given the limited near term DoD demand for continuous fiber reinforced CMCs, and the even more limited demand for continuous alumina-based fiber within that market, the U.S. industrial base is adequate for DoD needs.

3.2.5 CMC Government Programs³⁸

Aerospace programs, where improved structural performance at minimal weight penalties are the motivation, provide the incentive for CMC development. Major U.S. gas turbine engine suppliers for aircraft have teamed with DoD and NASA on the IHPTET program for future military aviation engines. Recently, the IHPTET engine companies have formed a Fiber Consortium that will support process development of fiber types that will have common application to the companies' composite programs. Initial Consortium projects are already underway. Actual CMC development within IHPTET itself, however, is set for later stages in the program and is currently not a major focus.

NASA is overseeing CMC and fiber development programs as part of the Enabling Propulsion Materials Program and the more basic High Temperature Engine Materials Program.

³⁴ Karnitz and Lowden.

³⁵ David Wilson, 3M Company, 1993.

³⁶ Karnitz and Lowden.

³⁷ Richard Goettler, Babcock and Wilcox, 1994.

³⁸ Information from the proceedings of the Interagency Coordinating Committee on Structural Ceramics, May 1994 meeting.

These programs are primarily aimed at composite materials for use in future airliner engines. New generation engines, especially those destined to power the HSCT, must not only meet the commercial airlines' need for performance and economical operation, but do so while meeting new regulations regarding aircraft noise and upper atmosphere emissions. If these regulations cannot be met, then the probability of the HSCT becoming a commercial reality will be greatly reduced. More specialized programs within NASA are developing CMCs for space power and propulsion applications, including hypersonics.

For a number of years, core programs in the Air Force have been examining new compositions and processes for ceramic fibers and composites. Again, propulsion systems needing enhanced high temperature mechanical capabilities are the major potential applications. Wright Laboratories has undertaken basic investigations into CMC behavior and stability, while working with ARPA to demonstrate CMC nozzle flaps and seals for the F-110 engine. The Air Force is also conducting CMC prototyping work for the F-119 engine, while R&D continues for rocket propulsion, thermal materials for a Single-Stage-to-Orbit vehicle, and exhaust impinged structures for the B-2. Navy studies in CMCs reflect its interest in shipboard environments, hence engine component materials work at the Naval Air Warfare Center has specifically looked at corrosion effects.

There are several CMC-related programs in ARPA. The Ceramic Insertion Program, which includes nozzle flaps/seals work on the F-110 engine with the Air Force that has been previously referenced. In addition, nozzle seals insertion is also taking place for the F-100 engine. A major ARPA effort is underway in its University Research Initiative, using micromechanism-based approaches to design of both CMCs and other high temperature composites. The first set of ARPA Materials Partnerships programs also includes some CMC development, including a Virtual Corporation in Low Cost Ceramic Composites for an interstage turbine seal. A separate ARPA program is fabricating and evaluating CMC components for a tactical missile turbine engine, while another is examining a novel method of fabricating "fibrous monoliths." These latter are spun, polymer-derived fibers that can be prespun and formed into shape without matrix additions before pyrolysis.

The DoE has been a longtime supporter of high temperature materials development, especially monolithic ceramics for vehicle engine components. More recently, DoE has begun an additional program to develop applications for continuous fiber ceramic composites (CFCCs) in industrial, ground based systems such as heat exchangers, burners, and gas turbines. The overall goal is to reduce the cost of ceramic composites by significantly increasing their usage. Commercial end users of ceramic composites and their fibers have even greater cost sensitivities than has traditionally been the case for purely defense oriented markets. The potential industrial markets for CFCCs and the fibers that reinforce them, can have a direct benefit on the capabilities, availability and costs for these materials to DoD. The CFCC program is now in transition to Phase II activities that are more directly tied to fabrication capability for end-user component needs. The significant crossover potential with DoD programs has been recognized in both DoE and DoD, such that technical coordination between the two departments for CMCs has become routine.

In the Commerce Department, the National Institute of Standards and Technology (NIST) has been performing supporting work to some of the other government programs mentioned above, including modeling of failure mechanisms, basic materials characterization studies, and test standards development.

3.2.6 CMC Assessment

The large scale demand forecast in the mid 1980s for advanced structural ceramic products did not materialize. In fact, outside of electronic ceramics (a \$4 billion market), the advanced ceramic industrial base is small, fragile, and in some cases, embryonic. Therefore, this study was undertaken to identify potential issues of DoD's assured, affordable access to CMCs.

This assessment found that, to a large extent, DoD will be able to leverage relevant civilian programs that are developing discontinuous CMCs for industrial/commercial applications and DoE programs that are developing continuous CMC applications for power generation and incineration. Although design specific requirements between civilian, industrial and defense systems that would use CMCs may differ (DoD applications may require higher operating temperatures, while civilian aircraft may emphasize longer service lifetimes), both applications will in all likelihood use common materials manufacturing bases and similar manufacturing processes.

Several elements of the CMC industrial base were considered in this study -- ceramic powders, discontinuous CMC fabricators, continuous fiber reinforced CMC fabricators, and the continuous silicon carbide reinforced fibers themselves. The following four paragraphs summarize findings in each of these areas.

Ceramic powders, used to form CMC matrices, are common to both the discontinuously reinforced and the continuous fiber industry. In some cases, these are the same types of powder used to manufacture monolithic structural ceramics. However, high performance CMC and ceramic components generally require specialized powders, with very high purity and highly uniform grain size and shape. Because these powders are related to the powders needed for the much larger market for structural ceramics, a solid U.S. base (along with France and Japan) for specialized powders is expected to emerge as demand grows. While DoD may drive requirements for specialized powders, it will nevertheless benefit from a large, commercially oriented, globally integrated production base. No immediate issues of access are apparent.

Discontinuously reinforced CMCs are an extension of high performance monolithic ceramics technology and consequently the industrial base for these materials is an extension of the existing monolithic ceramics industry. Therefore, the industrial base for particulate reinforced ceramics is relatively mature. The market for cutting tools and wear parts that encompasses this class of ceramic composites was estimated to account for most of the \$475 million U.S. market in 1994. The facilities, equipment, and trained people needed to produce

products of specific interest to DoD should remain available. This does not preclude potential insertion projects, if the benefits to DoD can be quantified.

There are many companies involved in the fabrication of continuously reinforced composites with several of them being relatively large and financially stable. Those large companies can afford to develop niche markets if they believe that there are profits to be made. Given DoE and NASA programs in this area, such niche markets will likely emerge. Therefore no issues of access are anticipated. However, even if an issue were anticipated, because there are so many fabricator companies in so small a market, there undoubtedly will be changes in this highly competitive area and consequently it is premature to take any major actions at this time. As was the case above, this also does not preclude potential insertion projects, if the benefits to DoD can be quantified.

Continuous silicon carbide fibers are used as reinforcements in CMCs. For a decade, two Japanese companies have been the major suppliers of these fibers for R&D work in the United States and Europe. However, current Japanese fibers cannot operate in oxidizing environments above 2200°F and they degrade during the processing typical of many CMCs. Stronger, higher temperature-capable fibers are needed to meet the requirements of the IHPTET and HSCT programs. While the Japanese are known to be developing fibers with improved high temperature properties, there is some question whether these programs will meet IHPTET and HSCT requirements and there is concern about potential costs for the new fiber. The fiber development consortia associated with the IHPTET and HSCT programs are relying on U.S. companies and universities. Technical successes and scale-up feasibility of these U.S.-derived fibers may lead to the establishment of production capabilities in the United States. Consequently, continued R&D seems to be the main avenue for sustaining DoD's access to this technology.

3.3 Metal Matrix Composites (MMCs)

3.3.1 MMC Overview

Metal matrix composites consist of two or more constituent materials, typically including metallic matrices with metallic, ceramic, or carbon reinforcements in the form of continuous fibers, chopped fibers, or discrete particles or whiskers embedded in a metal or alloy. This reinforcement/matrix combination results in a structural material with improved mechanical and physical attributes relative to those of conventional materials. MMC properties such as weight, strength, stiffness and temperature tolerance can be tailored for specific engineering applications by changing the amount and orientation of the reinforcement or by changing the reinforcement coating. The type and amount of reinforcement also determines composite cost and the approach and cost of manufacturing. Common combinations include Al_2O_3 particles or fibers in aluminum; graphite (Gr) fiber (continuous or chopped) in aluminum, copper, or magnesium; SiC particles, whiskers, or fibers in aluminum or titanium; and SiC fibers in titanium aluminides.

For the purposes of this study it is important to distinguish between the two broad categories of MMCs: (1) those reinforced with continuous fiber (cMMCs) and (2) those reinforced with discontinuous fiber or particulates (dMMCs). This distinction is necessary because the two classes are technically different and the maturity of the technology and, therefore, the maturity of the industrial bases are different. Applications for each also differ, continuous fiber-reinforced composites being of particular interest in high performance aerospace applications. Table 3.12 provides a qualitative comparison of the properties of each.

Different material manufacturing processes and fabrication procedures are typically utilized for the two types of MMCs.³⁹ From a technical perspective, discontinuously reinforced MMCs generally have lower specific strengths and elastic moduli, and use conventional metal forming techniques such as casting, rolling, and forging to fabricate components. A typical processing and fabrication sequence for dMMCs includes selection of the matrix and reinforcement (chopped fibers, whiskers, flakes or particles) and, possibly, a reinforcement coating. One of a number of casting, powder metallurgy (P/M), or *in situ* processes is then selected to produce a product form. The reinforcements are randomly oriented in the composite and the material is typically isotropic. Initial product forms may be ingots, billets, pellets, sheets, beams, slabs, or near net shapes. These product forms can often be further worked via casting, forging, extrusion, milling, machining, joining, or welding, though not necessarily by using conventional metal working techniques.

³⁹ J. Sater, "Federal Materials R&D: A Metal Matrix Composites Overview," 4th International Conference on Aluminum Alloys. Their Physical and Mechanical Properties, Conference Proceedings, Vol III, Georgia Institute of Technology: Atlanta, GA, pp.90-129.

Table 3.12 - Qualitative Comparison of Discontinuous and Continuous MMC Properties

Discontinuous MMCs	Continuous MMCs
<ul style="list-style-type: none"> • Property Improvements Over Matrix by $<2X$ • Improved Properties Over Monolithic Alloy <ul style="list-style-type: none"> (a) good wear resistance (b) high stiffness (c) sometimes low toughness (d) moderate strength (e) isotropic • Tailorable Properties <ul style="list-style-type: none"> (a) mechanical (b) physical • Lower Cost to Manufacture • More Reliance on Matrix • Net Shape Processes Utilized for Higher Reinforcement Contents • Conventional Methods to Produce Wrought Products for lower Reinforcement Contents • Structural Applications Are Generally Reinforced less than 25 percent Volume 	<ul style="list-style-type: none"> • Improved Properties Over Monolithic Alloy <ul style="list-style-type: none"> (a) high stiffness (b) high toughness (c) high strength (d) anisotropic • Tailorable Properties <ul style="list-style-type: none"> (a) mechanical (b) physical • Expensive to Manufacture • Requires Accurate Fiber Placement • Usually Net or Near Net Shape • Thermal Conductivity/Management Applications • High Temperature Applications
Revised from Source: Technology Base Enhancement Program Metal Matrix Composites, The North American Defense Industrial Base Organization, August 1993.	

Continuously reinforced MMCs, on the other hand, use more complex and expensive fabrication techniques to make components. From an industrial base perspective, discontinuous MMCs are closer to market acceptance and have a more substantial production base. Reinforcement forms for the cMMCs—large diameter fibers (greater than 100 μm), multi-filament tows (less than 20 μm diameter fibers), or metal wires—are often coated via a chemical or physical vapor deposition process after which they are fabricated into a preform before the fibers are integrated with the matrix material. Preforms can be green tapes, laminated tapes, thermal sprayed tape, infiltrated wire or tapes, etc. Other processes for manufacturing cMMCs can include casting, thermal spraying, powder cloth, or foil-fiber-foil processes, among others. Secondary fabrication processes for the cMMCs are much more limited: e.g., the presence of the fibers makes any deformation process such as forging or extrusion essentially impossible. Product forms are typically limited to thin-walled or sheet products or near net shape components. As one might expect, no single process is useful for all materials or application. While a large number of processes have been developed for the fabrication of MMC materials

and components, few are considered to have reached a production level. In addition, issues associated with recycling and reclamation are of concern since the ability to recycle and/or reclaim these materials is likely to affect their use. Processing efforts so far appear to be focused solely on process generated scrap from discontinuous SiC- or Al₂O₃-reinforced aluminum composites.

DoD demand for MMCs has the potential for very rapid growth as a result of the vast number of possible military applications. However, these materials are very expensive because of a lack of mature commercial markets -- commercial applications for dMMCs are just now beginning to materialize and the industrial base for cMMCs is still in a precompetitive stage. Therefore, until commercial use becomes more prevalent, the high cost of these materials will impinge on potential demand. In light of this situation, this assessment was undertaken to identify potential issues of assured, affordable access to MMCs for satisfying military needs.

3.3.2 MMC Demand

Because MMC markets are just emerging, demand is difficult to quantify, and sales projections are generally not available. The world market, excluding the FSU, was estimated to be 980,000 pounds in 1993, at a value of \$54 million. The benefits associated with MMC use include:

- Weight reduction
- Wear resistance
- Corrosion resistance
- Radiation resistance
- High strength
- Increased stiffness
- Tailorable thermal conductivity
- Elevated temperature capabilities

These benefits imply myriad potential defense and commercial uses, therefore demand is expected to rise in the future. For example, the annual global aerospace market for MMCs alone could reach \$100 million sometime beyond the year 2000 if they become more widely used in jet engine and subsonic and supersonic transport airframe components. The automotive market is potentially the largest volume market for low cost MMCs: 25 pounds of metal matrix composite per automobile could create a one billion pound per year market.⁴⁰ The following two sections discuss potential military and commercial demand respectively.

⁴⁰ Sources include K. Stevens, S. Fishman, J. Sater, "Part 3 Metal Matrix Composites," 1995 DoD/DoE/NASA Workshops on the U.S. Advanced Composites Industrial Base, DoD Ceramics Information Analysis Center, Draft, January 1995 and J. Sater, September 1994.

3.3.2.1 Military Applications

Incorporation of MMCs into weapon systems can provide the U.S. military with improvements in capability: increased range, payload, velocity, and maneuverability as a result of weight savings in airframes and engines; increased range, payload and improved target detection in missiles; improved transportability and mobility in combat vehicles; larger payloads and improved performance in space structures. All of these benefits would provide the military with enhanced warfighting capability and contribute to greater system affordability through lower life cycle costs and longer operational life. The following paragraphs discuss specific applications.

Aerospace: Aircraft engines (in particular gas turbine engines), airframes, spacecraft, and guided weapons represent the primary aerospace related application areas for MMCs. Aerospace manufacturers have conducted design and manufacturing analyses that have shown a potential weight savings of up to 60 percent for some components. More widespread use of MMCs in aerospace applications is likely to depend on life cycle cost, producibility, the range of mechanical properties that can be achieved, reliability and maintainability in service, material qualification via comprehensive testing and analysis programs, identification of a need for high reliability in extended use, and the ability to accurately predict component life. The most compelling near term DoD applications for MMCs are in propulsion systems -- turbine blades and vanes, fan frames, and thrust vectoring nozzles. Landing gear on advanced aircraft may also use continuously reinforced aluminum matrix composites and titanium matrix composites (TMCs) where they afford reduced weight and increased environmental resistance. Other candidate applications include supersonic aircraft and hypersonic missile skins. MMCs containing discontinuous whiskers or particulate reinforcements may find application in stiffness-critical airframe components where enhanced fatigue or fracture resistance is not necessary. Examples include inertial guidance systems, rudders, escape hatches, and aircraft hydraulic systems. For hypersonic aircraft, TMCs and intermetallic matrix composites are of particular interest. There is interest in light weight, high stiffness, high thermal conductivity materials for spacecraft applications such as truss structures and radiators. Continuous boron fiber-reinforced aluminum is used for the tubular cargo bay struts in the mid fuselage section of the space shuttle orbiter vehicle.

Nuclear Propulsion: In some space nuclear power and propulsion system components, material selection will be driven by the requirement for long operational lifetime while generating several hundred kilowatts of power, specific strength, creep and high temperature properties, thermal fatigue, thermal conductivity, resistance to aggressive environments, reliability and durability. This is also true for pressure vessels, heat pipes, and regenerators. MMCs of interest include various titanium-aluminide composites as well as more exotic, reinforced superalloys.

Guided Weapons: Stiffness designed components, such as fins, represent the most suitable applications for MMCs in guided weapons. Many MMC fins have been produced, but purely as test components at this time. MMCs have been introduced into some nonstructural

applications in guided weapons as well. The Trident missile uses a discontinuous SiC-reinforced MMC for guidance components previously made of beryllium. Tailorable coefficient of thermal expansion and lower cost were the drivers for this application. MMCs have been investigated to replace microwave packaging components made from Kovar. These applications are limited, but MMCs meet some critical needs and offer potential cost reductions related to guided weapons.

Armor: MMC armor applications are being driven by the need for light weight materials that offer high stiffness, a higher damage tolerance than ceramics, low cost, and large shapes. Armor applications for MMCs include armored vehicles, aircraft armor and personnel armor. The potential benefits that the material can provide are extensive. Lawrence Livermore National Laboratory developed a manufacturing process to bind boron carbide particles in an aluminum matrix to produce an MMC for armor applications as well as other applications. This material is currently being used for lightweight armor in U.S. Air Force special operations aircraft. While this application could cut the weight of an aircraft by up to 3000 pounds, its use is limited due to its high cost -- \$20 per pound. Lanxide has developed two materials for armor applications. They are currently testing these materials to determine performance characteristics and market viability. This market will be slow to develop due to limited military combat vehicle acquisition programs. The cost effectiveness of this material still needs to be proven.

Electronics/Thermal Management: The electronics/thermal management market for MMCs is focused on products requiring low density materials with high thermal conductivity, low or tailorable coefficient of thermal expansion, high stiffness, and high temperature capability. Discontinuously reinforced aluminum and graphite fiber-reinforced metals are the primary MMC materials that provide these properties. Diamond particulate-reinforced aluminum is also being tested for some of the more demanding electronic applications. Applications for MMCs in this market include electronic packages, circuit board heat sinks, carrier heat sinks, and structural electronic products such as racks and chassis.

Tracked Vehicles: The Army has also looked at using MMCs for other applications, including gun barrels, tank mirror substrates, tracks, road wheels, engine components (pistons, liners, con rods), fire control stabilization systems, brake components, suspension components, and bridge components.

Marine: The Navy is considering MMCs for numerous marine applications. MMC use in ship engines would offer corrosion resistance and low magnetic signatures; MMC use in submarines and torpedoes would enable increased depth through lighter weight and increased compression strength. Ship structures such as masts, hulls, and radar antenna components are also potential application areas for MMCs.

Some MMCs are already being used in military applications. For example, prototypes that have been fabricated from MMCs for military applications include the following:

- Cruciform and bulkhead airframe for the Ballistic Missile Defense Organization Exoatmospheric Re-entry Interceptor System projectile to provide a 28 percent weight savings compared to carbon fiber epoxy baselines.

- Heat rejection/heat exchanger chip carrier and printed circuit board for Air Force high power electronic modules for circuit boards.
- Vertical tail stabilizer/ventral fin for the Air Force F-16.
- Pratt & Whitney, General Electric, and Allison demonstration turbine engine components.
- Spacecraft truss structures and joints

In addition, production runs of MMC components include the following:

- Repair patches on aircraft wings.
- Escape hatches on the C-141 aircraft.
- Optical and guidance system gimbals for inertial and ring laser gyro guidance systems.
- Missile fins, avionics racks, electronic packaging, and optical mounts.

3.3.2.2 Commercial Applications

There has not been widespread acceptance of MMCs as a viable engineering material, despite significant R&D. In fact, a substantial portion of the MMCs currently produced in the United States is for R&D, including demonstration projects. Their introduction into actual components has been sparse and fragmented, and no high volume markets currently exist. Entry criteria for commercial use of MMCs require they: (1) be cost effective and easily manufacturable at acceptable rates; (2) offer improved product performance, quality, or reliability, or allow for creative product designs that offer new market opportunities; (3) provide improved fuel economy and emissions standards, along with waste disposal and recycling requirements; and (4) allow products to be brought more quickly to the market -- from three to five years for automobile companies and from 10 to 15 years typical for aircraft companies. Nevertheless, a variety of applications for MMCs and their associated benefits have already been identified.⁴¹

Aerospace: The incorporation of MMCs in the production of engines and airframes is being considered for commercial aircraft as well as military aircraft, however there has been only limited activity in the commercial realm. Fiber-reinforced titanium is being considered for applications in aerospace engines such as fan disks, compressor casings, turbine disks, compressor blades, and stator vanes. Currently, the only commercial MMC use in airframes has been conducted in Europe. Space applications for MMCs focus on the production of thermally stable space structures. These structures have been produced from graphite-reinforced aluminum and can be manufactured to have near zero coefficient of thermal expansion. Boron/aluminum tubes produced by Amercom are used as support structures in the shuttle cargo bays. MMC antennas have been produced for use on the Hubble telescope as well as some satellites.

⁴¹ *Technology Base Enhancement Program Metal Matrix Composites*, The North American Defense Industrial Base Organization (NADIBO), August 1993.

Automotive: The automotive and light truck market (45 million vehicles annually) represents the largest potential material volume market for low cost MMCs. The MMC of primary interest for automobile components is discontinuously reinforced aluminum (DRA) because of its significantly lower cost and relative ease of fabrication as compared to continuously reinforced composites. Automotive manufacturers are currently testing MMC components for brake rotors, drive shafts, connecting rods, and cylinder liners. DRAs are being used by several automotive companies already.⁴² Toyota replaced a cast iron hub of a crankshaft damper pulley to reduce weight and engine vibration with a DRA hub: weight was reduced by 40 percent and crankshaft pulley weight by 20 percent; engine performance was enhanced due to faster rotation. Honda uses DRA cylinder liners (chopped fiber of 12 percent Al_2O_3 , 9 percent graphite) that are integrally cast with the aluminum engine block. Wear depth was reduced by two thirds relative to the aluminum alloy for the same weight but was the same as that of the cast iron at reduced weight (by 50 percent); cooling efficiency was improved. More widespread MMC use in automobiles is slow because the industry is price sensitive -- any cost increase in the production of the car must be well justified in reduced life cycle cost or improved performance. Secondary processing capabilities and material recyclability are two additional concerns of the automotive manufacturers.

Recreational: Recreational equipment is another potentially large market for MMCs, especially DRAs. Applications include bicycle frames and other bicycle components, golf clubs, and tennis rackets. The main properties driving the use of MMCs in these types of applications are low weight and high stiffness, resulting in improved performance. Material cost is less of an issue because consumers are often willing to pay higher prices for improved performance. Duralcan's MMC material is already being used in the production of aluminum mountain bike frames for Specialized Bicycle Components, Inc. About 70,000 of these frames, competitively priced at under \$1000, have been sold so far, and another 20,000 are expected to be sold in 1995. With approximately 25 million bicycles sold a year, and about half of them being produced for the high end consumer (\$600 or more) price range, the potential demand for this market is considerable. The average DRA bicycle frame weighs between three and four pounds. This represents a potential market of between 37.5 and 50 million pounds of DRA material per year.

Electronics/Thermal Management: The commercial electronics/thermal management market for MMCs is similar to the military market. One MMC producer estimated the total potential market for all electronic applications to be as much as 50 million pieces per year.⁴³ Current applications in this market consist primarily of R&D projects.

Precision Equipment: Precision equipment applications are emerging, potentially large markets for MMC use. Precision industrial equipment manufacturers generally have common requirements for materials: light weight, high stiffness, long term dimensional stability, low

⁴² J. Sater, "Federal Materials R&D: A Metal Matrix Composites Overview," 4th International Conference on Aluminum Alloys, Their Physical and Mechanical Properties, Conference Proceedings, Vol III, Georgia Institute of Technology: Atlanta, GA, pp. 90-129.

⁴³ Ibid.

coefficient of thermal expansion, high thermal conductivity, high strength, high wear resistance, and high vibration damping. The continuing demand for improved precision, accuracy, quality, and productivity is pushing the limits of current materials. MMC material properties can provide improved accuracy, repeatability, speed, and payload capacity. Specific precision equipment applications for MMCs include machine tools, robots, motion control equipment, optical mirrors, platforms and associated hardware, photolithography machines, and coordinated measuring machines.

3.3.3 MMC Industry Structure

Producers

MMC production capability refers to the capacity for the reinforcement, matrix, and primary and secondary manufacturing processes. Some of the processing procedures, particularly for production of continuously reinforced MMCs, are new and only a single pilot plant exists. For discontinuously reinforced composites, however, processes are more mature and may be able to use facilities required for other materials.

Table 3.13 lists the known leading producers of metal matrix composites. As Table 3.13 indicates, there are 24 North American MMC companies, as well as four in Japan and one each in the UK, Germany, France, and Switzerland. In total, these 32 companies account for an estimated world market of \$54 million in 1993. The 24 North American companies, many of them small, are listed in Table 3.14 with their production capacity if known.

Table 3.13 - Companies Involved With MMC Production	
JAPAN	UNITED KINGDOM
Honda	Rolls Royce
Mitsubishi Heavy Industries	
Toyota	SWITZERLAND
Sumitomo	Alusuisse
GERMANY	FRANCE
MTU	Pechiney
NORTH AMERICA	
24 Companies	
Revised from Source: F. Carvalho, Department of Commerce, Office of Foreign Availability, March 1993	

**Table 3.14 - Known North American Metal Matrix Composite
Production Capacities**

Company	Material	Sales Vol./ Year (lb or units/year)	Production Capacity (lb or units/year)
Alcoa	Low and high volume SiC _p /Al	15k lb 1000 parts	500k - 800k lb 10k - 30k units
Amercom/ARC (Atlantic Research Corporation)	B, Gr, or SiC fiber in Al, Cu, Ti, or orthorhombic alloys	400 lb B/Al per Space Shuttle minimal other	3600 sheets (32 in x 122 in) 200k units
Ametek	Mo or W in Cu (P/M) (thermal management)	Proprietary	Proprietary
ARC-IMT (Industrial Materials Technology)	TMCs (SiC fibers in Ti)	100-200 lb	4000-5000 lb
California Consolidated Technology, Inc.	SiC _p in Al	250k-300k lb	10 ⁶ lb
Ceramics Process Systems Corporation	Low Volume SiC _p /Al	Proprietary	Proprietary
CKC (Ceramics Kingston Ceramiques)	SiC _w /Al	Minimal 100% T&E	Minimal
Composites, Inc.	SiC fibers in Al or Ti	-150 lb	-1000 lb
Cordec Corporation	Gr or SiC fiber in Al, Cu, or Mg	Proprietary	Proprietary
Duralcan USA/Alcan	Low Volume Al ₂ O _{3p} or SiC _p in Al	10 ⁶ lb	25x10 ⁶ lb
DWA Composites Specialties	SiC _p /Al (P/M) Gr fiber in Al, Cu, or Mg	Proprietary	150k lbs 1000-5000 lb 3000-5000 lb
Foster-Miller, Inc.	Gr fiber or SiC chopped fiber in Al or Mg	<200 lb (R&D, internal)	<200 lb
GM/ART (Advanced Refractories Technologies)	SiC _w /Al	Proprietary	>2000 lb
Howmet	SiC fiber in titanium XD TM TiAl	Minimal -- development 5k to 7.5k lb (projected estimate)	Minimal -- development <10% total production (XD TM TiAl produced on same line as Ti)
Lanxide Composites	Low and high volume Al ₂ O _{3p} and SiC _p in Al (PRIMEX CAST TM)	Proprietary	300k lbs scaling up to 1.5x10 ⁶ lb (expandable to 3x10 ⁶ lb)
Lytron Incorporated	Gr or SiC fiber in Al	Proprietary	Proprietary
MCT (Joint GM/Hitchner)	SiC _w /Al	Minimal -- development	Minimal -- development
MI-Tech Metals, Inc.	W in Cu (thermal management)	125k lb	250k lb
PCC Composites, Inc.	SiC _p in Al, Cu, or Mg Gr fiber in Al or Cu	4500 lb	10k lb
SPARTA, Inc.	Gr fiber in Al or Cu, diamond in Al	Proprietary	Proprietary
Textron Specialty Metals	B fiber in Al, SiC fiber in Ti and alloys	800 lb 100% T&E	2000 lb
3M	Al ₂ O ₃ fiber in Al, SiC fiber in Ti	Minimal 100% T&E	Minimal
Wisconsin Centrifugal	TiC in aluminum bronze, SiC _p in Al	Proprietary	Proprietary

Revised from Sources: Directory of the U.S. Metal Matrix Composites Industry, DoD MMC Information Analysis Center, October 1994; and Technology Base Enhancement Program Metal Matrix Composites, The North American Defense Industrial Base Organization, August 1993.

The current industrial situation in the U.S. represents a change from the situation before 1988 when only four companies -- Duralcan USA, INCO, Allied-Signal and Alcoa -- were fully facilitized, and three companies -- ACMC, DWA Composites and Lanxide Corporation -- were partially facilitized. Notwithstanding the growth in the number of companies, two of the early pioneers in MMC production, INCO and Allied-Signal, exited the MMC business in 1993. It should be noted that the particulate reinforced dMMC capacity indicated in Table 3.14 far exceeds actual production, especially for Duralcan. Only Advanced Refractories Technologies has a significant effort in whisker reinforced dMMCs.

The major sources of foreign competition to the North American MMC industry are Japan and Europe, primarily the United Kingdom. The Japanese, in particular, have directed their efforts toward commercial automotive applications with a strong emphasis on processing and process economics, particularly for dMMCs. In addition, Japanese firms appear willing to make the necessary capital investments and pay a 10 to 15 percent premium to gain production experience with the materials. Europe has shown extensive interest in MMC technology for both automotive and aerospace applications.⁴⁴ Airbus Industries is considering incorporating MMC material on their aircraft. A consortium consisting of Alcan, Fiat, and Cambridge is investigating the forging of DRAs, whereas another consortium (made up of Rolls Royce, Snecma, Fiat, Defense Research Agency, and AEA EUCLID) was formed to develop TMC production capability.⁴⁵ These are both European Community EUREKA programs aimed at developing MMC technology. EUREKA programs are characterized by a bottom-up approach, in which the government identifies very broad technical areas such as "advanced materials" and industry groups form consortia to respond with specific projects of interest to them. Japanese or European success in establishing high quality, reliable MMC components prior to North American manufacturers will create an advantage in maintaining a viable MMC industry, particularly for the dMMCs. In the U.S., General Motors has recently formed two joint ventures to produce dMMC automotive components: one is with Advanced Refractories Technology Corporation, the other with Hitchner Corporation.

Barriers to increased commercial and defense usage and demand can be grouped into one of two categories: technical and economic. Despite the fact that over \$500 million has been spent on MMCs by government and industry in the past 15 years, there are still numerous technical problems related to fundamental understanding, production, manufacturing, and use of MMCs that give designers pause in specifying them. The primary technical barriers preventing current MMCs from being more widely used are summarized as follows:⁴⁶

- MMC material characteristics and product inconsistencies;
- Lack of adequate materials, design, and processing databases;

⁴⁴ K. Stevens, et al., January 1995

⁴⁵ TMC research and turbine engine component development for the European EUCLID advanced turbine engine consortium program and for Rolls Royce will be conducted at the British Defense Research Agency Laboratory in Farnborough. Rolls Royce's recent purchase of Allison Turbine Engine Company, with its attendant TMC expertise, will establish a significant competition to the other U.S.-owned turbine engine companies.

⁴⁶ K. Stevens, et al., January 1995.

- Lack of adequate standards for materials, processing methods, and inspection and testing/qualification procedures;
- Lack of intelligent processing or integrated product and process development approaches;
- Lack of appropriate design and reliable analytical modeling techniques;
- Lack of low cost/high volume fabrication processes, especially near net shape processes;
- Lack of environmentally clean materials, processes, and manufacturing approaches in the form of recyclable materials, recycling processes, and low energy or alternative processes;
- Lack of joining, assembly, and reliable repair techniques; and
- Inexperienced labor and inadequate education related to MMC manufacturing and fabrication.

Major economic barriers⁴⁷, and the principal constraints to pervasive use of MMCs, include (1) the cost of producing MMC materials and components and (2) small to non-existent markets. The high final component cost which comes about from relatively expensive raw materials and complex processing methods is an issue for both dMMCs and cMMCs and is of particular concern for DoD. The dMMCs are relatively low cost (a few dollars per pound for cast discontinuously reinforced aluminum (DRAs) to about \$35 (range from \$10 to \$75) per pound for the P/M DRAs) but are often unable to meet the necessary performance requirements. The cMMCs, on the other hand, exhibit the highest performance but are quite expensive, on the order of \$5000 or more per pound.⁴⁸ The high cost of producing cMMC materials and the resultant high prices at which components are sold as well as the fact that there are few substitutes with comparable performance characteristics mean a user cannot easily respond to changes in price, i.e., demand is inelastic. A low elasticity implies that the reduction in price needed to increase use of the material is large, which, in turn, suggests that improved performance capabilities may be insufficient to bring about a market increase. One way to address this issue may be to evaluate the system life cycle cost against MMC component acquisition cost.

Other economic barriers include: the high costs associated with and long time required for MMC R&D and scale-up to production weighed against the risk of failure; the high cost of capital facilities and the lack of incentives to invest in them; short term management goals (profit considerations); government procurement and funding policies; and government funding uncertainties created by an annual budget cycle.

⁴⁷ Ibid.

⁴⁸ Note that for a civil aircraft program, processing and manufacturing represent about 60 percent of total cost. For MMCs to be used in such aircraft the cost of the component must be \$500 or less per pound. The cost goal for finished automobile components is typically less than \$5 per pound.

Monofilament Fiber Suppliers

Despite efforts to use MMC components in greater quantities, the industrial base for SiC monofilaments is not well established. The current market for SiC monofilaments consists mainly of R&D programs to develop and demonstrate MMCs. Requirements from these efforts have been insufficient to justify investment in large scale fiber production facilities. As a result, fiber prices are quite high, on the order of \$1500 to \$5000 per pound. With steady production, it is believed possible to reduce prices to \$1000 per pound. In any case, the market may never develop to what is generally viewed as a traditional scale production size. The industry may remain the size typically associated with a niche market.

Textron Specialty Materials has the only currently established domestic production capability for SiC monofilaments. Textron makes the widely used SCS-6 fiber (140 micron diameter) as well as SCS-2, -9, and -10. These fibers are made by chemical vapor deposition of SiC around a carbon core, following which a variety of coatings can be applied. Textron is also known to be developing an improved monofilament (SCS-Ultra) with reported room temperature tensile strengths up to one million pounds per square inch. Atlantic Research Corporation's (ARC) subsidiary, Amercom, is emerging as another domestic source for SiC monofilaments. ARC is active in the IHPTET Fiber Consortium, which may develop new fibers.

Textron, however, generally does not sell its SiC fiber, preferring instead to sell fabricated MMC components. Because of Textron's proprietary rights position and because its fiber has very good properties, customers generally accept these terms. Consequently, by discouraging the entry of potential MMC fabricators, Textron's policy may actually retard process development and the growth of the MMC market.

The Sigma monofilament is a potential foreign competitor to Textron's SCS-6 fiber. Sigma and SCS-6 have comparable tensile strengths and moduli but Sigma has a higher density and smaller fiber diameter (100 microns). Sigma, which has been produced by Berghof in Germany and by British Petroleum in the UK, is made by chemical vapor deposition of SiC on a tungsten core. As mentioned previously, production capabilities for Sigma fibers currently reside within the Defense Research Agency at Farnborough, England. The Japanese evidently do not produce SiC monofilaments, although the Tokai Carbon Company has been reported to make a SiC fiber of unknown diameter via chemical vapor deposition. The Japanese have used Textron's fiber in some research programs, however. For example, MITI's High Performance Materials for Severe Environments program utilized Textron's SiC to reinforce titanium-aluminide matrices. In another program, goals were initially achieved by utilizing Textron's SCS-2 and SCS-6 fibers. Goals were then lowered so that the project could be completed utilizing Japanese made fibers.

The lack of a manufacturing infrastructure to produce MMC components contributes to the nonavailability of MMCs for broader use. This in turn contributes to the cost versus volume issue: costs would come down if volume increased, volume would increase if costs would come

down. The two main cost drivers affecting the final MMC product are raw materials and processing methods.

Whiskers

Whiskers are short fibers with small diameters, usually less than 1.5 microns. Their aspect ratios (length to diameter) range in value from 30 to 100. Whiskers (as opposed to chopped fibers) are grown as single crystals and exhibit extraordinary strength and stiffness. They are also very expensive, costing several hundred dollars per pound,⁴⁹ and are used as reinforcements for both MMCs and CMCs.

In North America, there are a number of whisker producers:

- Advanced Refractory Technologies (ART) manufactures silicon carbide whiskers. ART has been supported by General Motors for six years in the development of lower cost whiskers for use in MMCs.⁵⁰
- Ceramics Kingston Ceramiques is a Canadian company producing MMCs as well as silicon carbide whiskers.
- SiC whiskers are also available from Los Alamos National Laboratory.
- Boron carbide whiskers are made by Third Millennium Technologies.
- Advanced Composite Materials Corporation (ACMC) has manufactured silicon carbide whiskers in the U.S.⁵¹

While the previous paragraph identifies several potential producers of SiC whiskers, this industrial base, with the exception of ACMC, is immature and fragile, involving only small companies.⁵² ACMC is currently supplying SiC whisker for CMC cutting tools. Its willingness and capacity to supply whisker for MMCs is not clear. Commodity level volume requirements for SiC whiskers for MMCs have not yet materialized.

Japanese companies have been the major commercial suppliers of silicon carbide and silicon nitride whiskers during the past decade.⁵³ The major producers of SiC whiskers are

⁴⁹ Whiskers are considered a carcinogen requiring special handling, adding to the already high processing costs.

⁵⁰ See the 1993 NADIBO study, p. 80.

⁵¹ ACMC is owned by Tateho Chemical Industries Co. of Japan. Its corporate plans about producing whiskers in the future are unknown.

⁵² For example, the 1993 NADIBO study (p.80) found that potential users perceive SiC whiskers to be in limited supply.

⁵³ JTEC, "Advanced Composites in Japan," March 1991.

Tateho (which owns APMC) and Tokai Carbon. Tokai's whiskers are distributed in the U.S. by Textron. Ube Industries supplies high quality silicon nitride whiskers. Other types are manufactured by Otsuka Chemical, Mitsubishi Mining and Cement, and Shikoko Chemicals.⁵⁴

3.3.4 MMC Government Programs

U.S. government supported efforts have focused primarily on applications with extreme temperature and mechanical property requirements, rather than on lower performance materials with wider application. Several of the more important programs are described below.

If MMCs are to be utilized in military systems, the availability of consistent, high quality, lower cost material is essential. The Continuous Fiber Metal Matrix Composites Model Factory program (3M-prime) was initiated in 1990 to address issues associated with processing, quality, and cost of MMCs for high performance, defense related applications. The goal of the program was to develop a flexible process capable of producing high quality MMC materials at low cost and volume -- i.e., any fiber and matrix material could be combined on the same production line and, by use of intelligent process control, small volumes of consistent, high quality MMCs could be produced at potentially lower cost. The program is currently focused on SiC/Ti composite production using a dense monotape concept primarily for turbine engine applications and on Al₂O₃/Al composite production by pressure casting for a variety of structural applications.

The Titanium Matrix Composite Turbine Engine Component Consortium (TMCTECC)⁵⁵ program, initiated in 1994, is focused on developing specific turbine engine component applications -- a reinforced hollow fan blade and a reinforced fan frame -- for military engines produced by Pratt & Whitney and General Electric, respectively. Goals for Phase 1 for the materials suppliers include demonstrating maturity of the MMC material and component manufacturing processes (especially a detailed manufacturing plan and fabrication of 100 lb of material in a minimum of three batches); demonstrating ability to meet technical requirements for the two components; demonstrating cost effective processing strategies (includes cost models projecting \$500 per pound of TMC material in the right form for the applications and based on a production level of 15,000 pounds per year by September 1998 and cost model evaluation by independent third party). Other goals include: examining projected component fabrication costs at or below that warranted for implementation via comparison to improved baseline monolithic components; demonstrating component fabrication through predicting shape and tolerances of the component and its behavior in an operational environment; and completing a positive cost-benefit business analysis through assessment of development and life cycle cost trade-offs with performance and projected markets. The selected applications are believed to demand a sufficient quantity of TMC material on an annual basis to profitably support a small vendor base.

⁵⁴ In an attempt to circumvent the high cost of SiC whiskers, the Nagoya Government Industrial Research Institute in Japan is developing a potassium titanate whisker. This whisker has lower properties than SiC but reportedly costs one-fiftieth as much. See Diefendorf, pp. 92-8.

⁵⁵ More information on this program is given in Section 3.3.5.

If the fan frame and fan blade components are successfully introduced, demand for TMCs is expected to increase, leading to a more sustainable and competitive industry.

While the capability exists to produce SiC monofilament to meet R&D and limited production requirements, it has not been scaled up for steady, high volume production. Domestic technology, as reflected in Textron's SCS family of fibers, is quite advanced. However, improved fibers are necessary to meet the demanding performance goals of IHPTET and other high performance applications. The IHPTET Fiber Consortium is developing improved high temperature fibers to enable both MMCs and CMCs to meet these goals. NASA's Advanced Fiber Technology initiative for the HSCT program is also developing improved fibers to meet high temperature requirements for MMCs and CMCs.

The North American Technology and Industrial Base Organization (NATIBO) conducted an assessment of the metal matrix composites industrial base in 1993. The study team was composed of the military services, Canada, industry, and academia. The assessment objective was to identify the potential for an emerging technology to continue to advance and remain viable in the current and projected economic environment. It concluded with a 10 year roadmap of specific recommendations for this technology to grow into a viable, usable product. One of the specific recommendations was to create a low cost MMC insertion program jointly funded by industry and government. The project has three phases: tank track shoes, AMRAAM seeker support structure, and diesel pistons. Under the first phase, the Army Tank Automotive Command (TACOM) is currently pursuing development and insertion of silicon carbide whisker-reinforced aluminum MMCs into their combat vehicle fleet. TACOM, in conjunction with NATIBO, awarded a three year, \$4.2 million dollar contract to develop and test squeeze-cast, selectively-reinforced aluminum MMCs for tracked vehicles. It is possible that these whisker-reinforced MMCs may be less expensive for tracked vehicles than particulate-reinforced MMCs.

3.3.5 MMC Assessment

DoD demand for MMCs has the potential for growth as a result of the vast number of possible military applications. However, these materials are very expensive because of a lack of mature commercial markets -- commercial applications for dMMCs are just now beginning to materialize and the industrial base for cMMCs is still in a precompetitive stage. Therefore, until commercial use becomes more prevalent, the high cost of these materials will impinge on potential DoD demand. In light of this situation, this assessment was undertaken to identify potential issues of assured, affordable access to MMCs for satisfying military needs.

This assessment found that there are potential issues of assured, affordable access. Industry is not capable of satisfying a high volume DoD demand for cMMCs, if it should materialize. In addition, low volume production costs are high. The large volume requirements needed to drive the material/component price down to a level necessary to generate affordable production (or a good return-on-investment) have not yet been achieved.

This assessment also found sufficient commercial capacity to supply dMMCs that will reduce the weight of military vehicles and, at the same time, maintain the capability to operate effectively in rugged environments. However, no clear, quantitative demand estimates were available. Until demand can be definitized, no assessment of affordability can be made.

The numerous technical and economic barriers to widespread MMC use identified in this assessment cannot be overcome by industry alone. Although industry and government together have made progress in material characterization, standards development for dMMCs, and modeling techniques, there has been little application specific investment to ensure an item is producible.

The identified barriers are not insurmountable however. Several actions need to take place:

- Lower the cost of producing and using MMCs.
- Overcome technical shortcomings, including continued characterization of the material as manufacturing processes mature.
- Improve commercial viability and increase commercial demand for MMCs to lower overall material cost for DoD.

The following describes a specific proposal that is intended to address the above barriers directly for cMMCs.

Continuous Fiber-Reinforced Metal Matrix Composites

Of the various combinations of fiber and matrices that make up the continuously reinforced class of metal matrix composites, the ones of current interest for defense are the silicon carbide fiber-reinforced titanium and titanium aluminide matrix alloys. These high temperature resistant composite materials are needed for the next generation military gas turbine engines and, ultimately, to maintain the competitive edge in commercial gas turbine engine industry. The technology for the titanium composites capable of operating up to 1000°F is believed to be in place such that significant additional R&D is not necessary⁵⁶ though cost and consistent quality are still issues. Industry representatives indicated a strong movement toward production is necessary a step that is not affordable for a single company working alone.⁵⁷ Cooperative partnerships are believed to be key in achieving this goal.

A government/industry partnership (TMCTECC) is in place to create a viable supplier base for both commercial and military applications for titanium matrix composites.

⁵⁶ Additional R&D is required before higher temperature titanium matrix composite variations are ready for application. However, the manufacturing base for the lower temperature versions of titanium matrix composites should also support the future high temperature titanium and titanium intermetallic matrix composites.

⁵⁷ K. Stevens, et al., January 1995.

Approximately \$150 to \$200 million, split equally between government and industry, is planned for this program. However, a portion of the government share has not yet been programmed. A proposal has been made to fund the balance of the government share (approximately \$20 to \$25 million) as a Defense Production Act Title III Project. This Title III initiative complements ARPA and the Military Services' efforts to develop and demonstrate the performance improvements resulting from titanium MMC applications in high performance turbine engines by reducing the technical and business risks. It will establish a low cost, domestic manufacturing capability for titanium MMCs and transition manufacturing technology from pilot scale production to full scale production. The military goals of this project are:

- (1) establish a long term, viable producer, in the 1997 to 2000 time frame, to meet the requirements of the F-119 engine for the DoD's F-22 and potentially for the Joint Advanced Strike Technology (JAST) program as well as the commercial 777 transport aircraft;

Approximately 1,050 F-119 engines are currently planned for production for the F-22 program.

- (2) lower the costs of titanium MMCs for the above programs and other potential insertion opportunities;

In the existing precompetitive TMC industrial base, production costs range between \$5,000 and \$10,000 per pound. The goal of this project is to reduce manufacturing costs to between \$500 and \$1,000 per pound.

- (3) lower life cycle costs;

Current plans call for the use of TMC reinforced actuator piston rods for the F-119 engines in the F-22. The finished TMC piston assemblies save 3.8 pounds per engine relative to a steel version. JAST planning factors indicate that a 100 pound weight reduction equates to approximately \$750 million in reduced operations and maintenance cost (principally fuel) over the life of 3,000 engines. If these planning factors are assumed also to be applicable to the F-22, the deployment of TMC actuator rods in the nozzle would project to a reduction in life cycle costs of something like \$10 million. Assuming the expected TMCTECC price reductions, production of TMC assemblies would be only \$3 million higher than steel rods in total. If successful in the engine, similar TMC systems could easily replace the current baseline steel systems being used for the F-22 to actuate components like the leading edge flaps, ailerons, and flaperons. If these were converted to use TMC rods, an additional weight savings of about 28 pounds per aircraft would accrue.⁵⁸

⁵⁸ Based on data provided by Pratt and Whitney.

The F-22 currently plans to use hollow titanium fan blades which are bonded onto the disk by inertia welding. The blades themselves weigh about 4.3 pounds before bonding and there are 22 of them on each fan rotor. Current costs for the fan stage are approaching one million dollars per engine. In an effort to reduce costs (to something in the typical fan rotor cost of about \$100,000), the F-119 is considering the use of solid titanium blades. However, the use of solid titanium blades would add 100 pounds or more of weight to each engine. Assuming TMCTECC is successful, hollow TMC fan blades could be used at near the cost of solid titanium blades and the potential 200 pounds (at two engines per aircraft) or more weight growth of the aircraft could be avoided.⁵⁹

The design of the F-119 engine has not been finalized. The above examples are possibilities allowed by the use of TMCs. If the TMCTECC program is successful and the Air Force allows continued modifications for improved performance and/or reduced cost, then TMCs would be a strong insertion candidate for not only the F-119 engine but also for the engine that will eventually be used on JAST.

(4) enhance defense capability.

The weight reductions resulting from the use of titanium MMCs in turbine engine components translate into improved range, increased payload, velocity, and maneuverability for fighter aircraft like the F-22. In addition, the extensive use of TMCs is generally thought to be enabling to the development and deployment of Advanced Short Take Off and Vertical Landing aircraft anticipated for demonstration in the JAST Program. Such capabilities would mitigate the need for large catapults on aircraft carriers and would facilitate operation from short or battle damaged airfields as well as a variety of other relatively unprepared sites. The use of TMCs in transports could lead to the development of a class of engines capable of developing 120,000 pounds of thrust or more. This improvement would facilitate the development of transports with either double the range of current aircraft carrying similar payloads, or double the payload at the same range.

Another emerging possibility is the use of TMCs to mitigate or eliminate fatigue failures in currently deployed fighters and transports. The major cause of failure and retirement in today's gas turbine powered fleet is fatigue. TMCs inherently exhibit far higher fatigue strength than comparable metallic materials so that TMC-enhanced parts can be designed to exhibit far greater life than metal components. Further, the high stiffness of TMCs allows them to be used as damping systems for currently deployed components such as blades, vanes and spacers. Such use could potentially reduce the number of engines and aircraft lost due to fatigue failures (along with the possible loss of life associated with such failures) as well as the maintenance costs associated with the routine repair and rework of in-service components.

⁵⁹ Ibid.

Conclusion

Military insertion projects (e.g., the NATIBO effort) potentially help to address many of the barriers to the widespread use of MMCs in DoD systems. They may make MMCs more attractive as a material of choice in that the increased demand may lead to larger scale (military and commercial) operations and consequently lower production costs. The above proposal not only addresses the barriers directly (by establishing facilities capable of high volume production) but also enables follow-on MMC insertion projects where the return-on-investment for DoD warrants MMC use.

3.4 High Conductivity Graphite Fiber Composite Thermal Management Materials

3.4.1 High Conductivity Material Overview

This section discusses specialized types of composite materials that are designed to transport heat as well as carry mechanical loads. Therefore, in addition to mechanical strength and stiffness requirements, these materials must provide high thermal conductivity and controlled thermal expansion. These attributes are provided by the general class of composites reinforced with continuous, high thermal conductivity graphite fibers. The use of such high thermal conductivity fibers has been made possible by continuous improvements in high thermal conductivity carbon based fiber over the past few years.

Historically, carbon fiber development focused on aircraft structural applications where high strength and high strain to failure were the desired properties. More recently, spacecraft requirements for high stiffness and dimensional stability provided emphasis for development of carbon based graphite fibers with high elastic moduli. An additional benefit, these fibers also exhibited extremely high thermal conductivity (two to three times that of copper) in the fiber direction. This fiber also has a negative coefficient of thermal expansion which allows for precise tailoring of thermal expansion of the finished polymer, metal, or carbon matrix composite material. Precise thermal expansion control can be vital to reducing thermal strain and distortion and is thereby vital to increasing the reliability of sensitive electronic and spacecraft systems.

This assessment was undertaken because emerging aircraft and electronic markets may impact on the cost and availability of high thermal conductivity material. If costs were to decrease, and availability were to increase, DoD applications might increase substantially, and consequently, issues of assured, affordable access might arise.

3.4.2 High Conductivity Material Demand

Applications being investigated for these engineered, high thermal conductivity materials are listed in Table 3.15.

Table 3.15 - High Thermal Conductivity Composite Applications			
APPLICATION MATERIAL	ELECTRICAL	SPACE	OTHER
Graphite*/Aluminum Graphite*/Copper	<ul style="list-style-type: none"> • Circuit board thermal planes • Constraint for circuit board • Chip radiators 	<ul style="list-style-type: none"> • Battery housings • Radiators • Antenna struts 	<ul style="list-style-type: none"> • Cryogenic conductors • Hypersonic missiles • Gun barrels
Graphite*/Polymer	<ul style="list-style-type: none"> • Circuit board thermal planes • Constraint for circuit board • Housings 	<ul style="list-style-type: none"> • Solar array panels • Thermal doubler/radiators • Antenna struts 	<ul style="list-style-type: none"> • Aircraft engine nacelles • Heat exchangers
Graphite*/Carbon	<ul style="list-style-type: none"> • Circuit board thermal planes • Constraint for circuit board • Chip radiators 	<ul style="list-style-type: none"> • Laser hardened structures • Radiators • Antenna struts 	<ul style="list-style-type: none"> • Brakes • Heat exchangers
* High Thermal Conductivity Graphite Fiber			

The following discusses these potential electrical, space, and aircraft applications in more detail.

Electrical Applications

Failure mechanisms of electrical devices and circuits of all kinds are temperature sensitive. Improved thermal performance translates to lower operating temperatures. In turn, lower operating temperature can be directly related to increased electrical system reliability which can pay large dividends in military systems. While the exact decrease in temperature and accompanying decrease in failure rate to be expected by utilizing high conductivity composites is a function of the particular circuit design and housing, the importance of achieving lower operating temperatures is clear.

Also, as a result of decreased operating temperature, increased device packing density and heat flux in terms of watts per unit area could be achieved without increasing the failure rate. As the packing density of electronic devices is increased, thermal management becomes more of a problem. SEMATECH's Packaging Roadmap predicts the heat generated per chip in personal computers will increase from 10 watts per chip now to 40 watts per chip in about 10 years. Over the same time frame SEMATECH predicts the heat generated in military electronics and commercial workstations will increase from the present day 20 watts per chip to 120 watts per chip. Not only is thermal management a growing problem, but any material that is included in a device package or circuit board laminate that undergoes large variations in temperature must work to match the thermal expansion of the electronic packages so that thermal cycling does not cause the interconnects to fail.

The typical solution to these problems today is to include a metallic thermal conductor in the electronic package or mounting board. Aluminum is the material of choice for many commercial applications where power dissipation is not a problem and operating temperature ranges are narrow. For more demanding thermal conditions encountered in military and high power commercial electronics, copper clad sheets of molybdenum or Invar are included in the mounting boards to constrain thermal expansion and promote thermal conduction. Similarly, materials such as copper-tungsten are utilized in electronic packaging for thermal management purposes.

Recent development work with high thermal conductivity composites has demonstrated options that offer lighter weight systems with equivalent thermal performance, better thermal performance at equivalent weight, or some combination of weight savings and thermal performance gain. Defense research and development programs have demonstrated the performance of high conductivity composites in the Standard Electronic Module - Format E (SEM-E) for use in military electronic hardware.⁶⁰

The market for just the copper-tungsten heat sink materials used in electronic packaging is projected to increase from \$25 million in 1993 to \$200 million in 1996.⁶¹ Even though the magnitude of the thermal management problem has been projected, and estimates for the growth of the copper tungsten segment of the market are available, there is insufficient data to quantify the overall size of the market for advanced thermal management materials.

Regardless of the lack of market data specific to thermal management materials, there is business activity based largely on past DoD research and development efforts in advanced composites. At the current time at least three companies are known to be considering the manufacture of thermal management components for electrical application based on high thermal conductivity composite materials. Albany International is manufacturing a composite heat sink that utilizes Amoco's high conductivity P120 fiber in a polymer matrix to control thermal expansion and increase thermal conductivity. Lockheed-Martin has selected this product for use on for the Army's RAH-66 Commanche helicopter and the material is being evaluated for a potential F-16 retrofit program. At this time the potential demand created by these applications is uncertain.

An upper limit on potential demand for thermal plane materials can be estimated based on current sales of thermal plane materials for high power electronics. The annual market for copper-invar-copper and copper molybdenum-copper material is estimated to be 25,000 pounds per year and 20,000 pounds per year, respectively. If both of these materials were displaced from the thermal management market by an equivalent volume of K1100/aluminum, the annual market for K1100/aluminum in this application would be between 11,000 and 12,000 pounds.

⁶⁰ Glatz, J., Whitley, W., and Hook, M., "Manufacture and Test of Advanced Composite Standard Electronic Modules," SAMPE, Vol. 6 (1992), p. 308-319. Kinna, M., "Development of Composite Materials for Electronic Packaging Applications" SAMPE, Vol. 6 (1992), p. 547-555.

⁶¹ Heat Sink Trip Report, Brad Botwin and Erin Finn to Sue Eckert, Department of Commerce, August 29, 1994.

Spacecraft Applications

Space applications are an important area of interest for high thermal conductivity composites. Due to the vacuum environment, heat transport must ultimately occur by radiation to deep space. At the same time, part of the spacecraft structure may be warmed by the sun if not protected by earth's shadow or appropriate reflective insulation. The net result is that thermal management and differential thermal expansion are primary considerations that must be taken into account when designing spacecraft. High thermal conductivity composites can help on both counts by decreasing thermal gradients and reducing thermal expansion.

Onboard mechanical and electrical equipment generate heat through frictional or resistance losses, respectively. Passive thermal management schemes that thermally conduct this heat to radiator panels are the simplest and most reliable way to keep spacecraft equipment within acceptable operating temperatures. Aluminum is frequently utilized for this purpose. For instance, Hughes Space and Communications Group's design for an Ultra High Frequency Follow-On Satellite contains a traveling wave tube that dissipates approximately 70 watts of power. An aluminum alloy plate (thermal doubler), weighing approximately six pounds, is utilized to draw heat away from the traveling wave tube and conduct it to the external radiator panel. A study performed by SPARTA, Inc. predicted that a thermal doubler made of high thermal conductivity carbon fiber in an aluminum matrix would meet all mechanical and thermal requirements at a saving of more than two kilograms for this one application.⁶² According to an estimate attributed to Ball Aerospace Systems Group, an extra two kilograms of expendables for station keeping allowed by the lighter weight thermal doubler would provide a two month life extension for a typical satellite. When the multi-million dollar costs of building and launching a new satellite are taken into account, the value of a two month life extension can reach into the hundreds of thousands of dollars.

Thermal management is one of the primary design considerations for spacecraft. As spacecraft become smaller, thermal management becomes even more of an issue. Passive means of heat rejection that eliminate weight and complexity are critical to the smaller spacecraft being considered for defense sensing and commercial communication applications. The commercial Iridium communications system proposes a 66 satellite constellation with a three per year replenishment rate. A typical satellite structure is less than 20 percent of the total spacecraft weight. Of this only a fraction will be the high thermal conductivity material needed for temperature control. Consequently, even a large constellation such as Iridium is not likely to require more than a few thousand pounds of the advanced thermal management materials.

⁶² Reference: J. Glatz and D. Vrable, "An Assessment of the Impact of Advanced High Thermal Conductivity Composite Materials on Satellite Components," 43rd Congress of the International Astronautical Federation, August 28 - September 5, 1992, Washington DC.

Aircraft Applications

High thermal conductivity composites are also finding applications in aircraft structure. Hexcel Co. utilized Amoco's P-120 pitch-based carbon fiber to develop a thermally conductive honeycomb -- their Conductive Core (TM) product. This material was selected by Boeing to transfer heat from the interior of the Boeing 777 engine nacelle.⁶³ Thermal conductivity, weight reduction, and corrosion resistance are said to be the attributes that led to the selection of the Hexcel composite material. No information is available on design details or comparisons with other materials considered by Boeing. Thus, in this analysis it is not possible to quantify the benefits of the high thermal conductivity material. Regardless, this selection by Boeing indicates confidence in the material and provides a significant commercial market for one of Amoco Performance Products higher thermal conductivity graphite fibers and for the thermally conductive honeycomb manufactured by Hexcel.

The only market information that has been obtained at the time of writing is that the Boeing 777 application will require several thousand pounds of fiber per year. More quantitative estimates are dependent on the Boeing 777 production rate. The suppliers involved note that the selection of Conductive Core (TM) for the Boeing 777 does open the door to other possible applications but no estimates are available at this time.

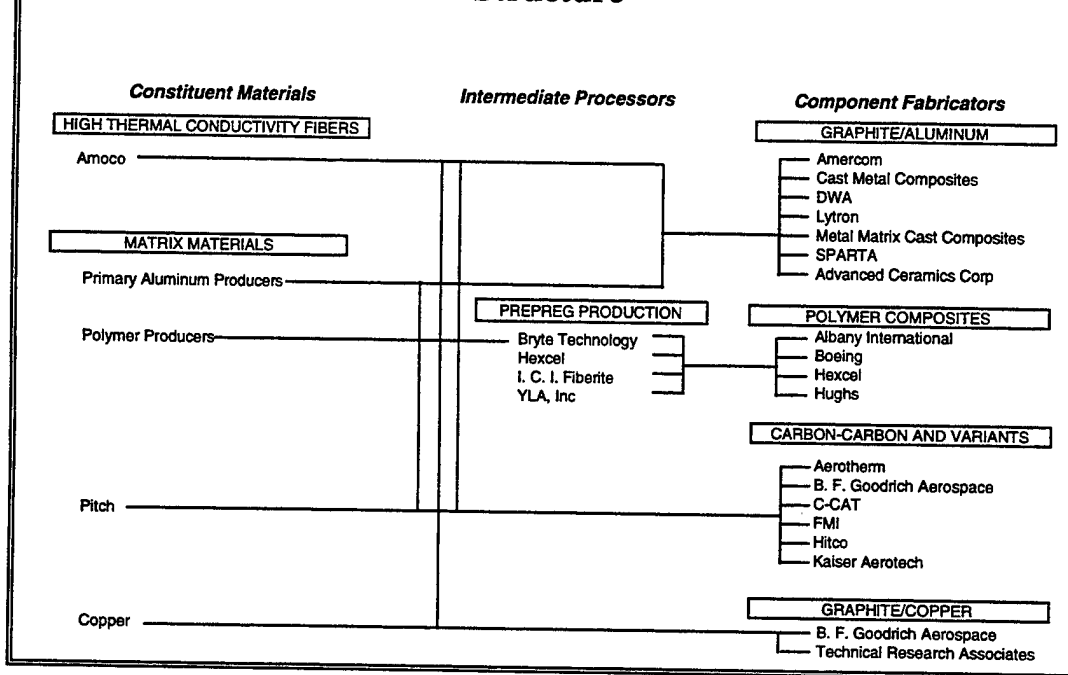
3.4.3 High Conductivity Material Industry Structure

The high thermal conductivity composites industry has not matured beyond the prototype stage. High thermal conductivity graphite fibers used for thermal management are dominated by Amoco's P120 and K1100 fibers. The former costs between \$800 and \$900 per pound; the latter sells for \$1750 per pound.

The structure of the industry as it exists today is illustrated in Figure 3.6. Aluminum, resin, and pitch materials are available from a host of large companies in the primary aluminum, chemicals, and petroleum business, respectively. In the case of polymer matrix composites, intermediate producers may be involved in the process of combining carbon fibers and polymer resins into prepreg products. Producers of stand-alone components that are marketed to others or utilized in their own products are listed on the right hand side of Figure 3.6.

⁶³ D.A. Schulz et al., "High Modulus Pitch-Based Graphite Yarn," AMOCO Report No F1004-2, Sept. 1994, pp. 23-24.

Figure 3.6 - High Thermal Conductivity Composites Industry Structure



3.4.4 High Conductivity Material Government Programs

Government support of high thermal conductivity composite research and development has been exclusively funded by the Department of Defense. Within DoD, the majority of the work has been sponsored by the Navy to address applications such as survivable spacecraft structure and thermal management of electronics and high temperature batteries. The Navy has supported all aspects of the technology from development of Amoco's ultra high thermal conductivity (K1100) fiber to fabrication of demonstration components for test and evaluation.

As a result of the Navy sponsored efforts, the feasibility of fabricating various types of high thermal conductivity composites has been demonstrated and initial materials property data bases and production processes have been established. The most recent effort (currently out for bid) is a program designed to establish teaming arrangements between fiber suppliers and component manufacturers to further develop military applications of high thermal conductivity composite materials.

3.4.5 High Conductivity Material Assessment

This assessment was undertaken because emerging aircraft and electronic markets may impact on the cost and availability of high thermal conductivity material. If costs were to decrease, and availability were to increase, DoD requirements might change, and consequently, issues of assured, affordable access might arise.

This study was unable to identify any issues of access, because the high thermal conductivity composites industry has not matured beyond the prototype stage. For the time being, cost appears to inhibit the use of high thermal conductivity composites for applications other than the few specific examples described in this section. The ultimate effect of the aircraft market on price and availability has yet to be determined; the aircraft market could become quite large if the high thermal conductivity material market expands beyond the Boeing 777 application. Similarly, it may be as much as ten years before the commercial electronics industry will require materials that have better thermal conductivity than those being used by the military today. Consequently, commercial development of new materials that may affect the price and availability of high thermal conductivity composites cannot be predicted at this time.

While the military has some immediate requirements, the applications are specialized and do not yet create a significant market. Today's requirements are being met by ultra high thermal conductivity materials. Any larger scale military use or eventual price reduction will depend on what happens in the commercial market.

CHAPTER 4: SUMMARY OF FINDINGS

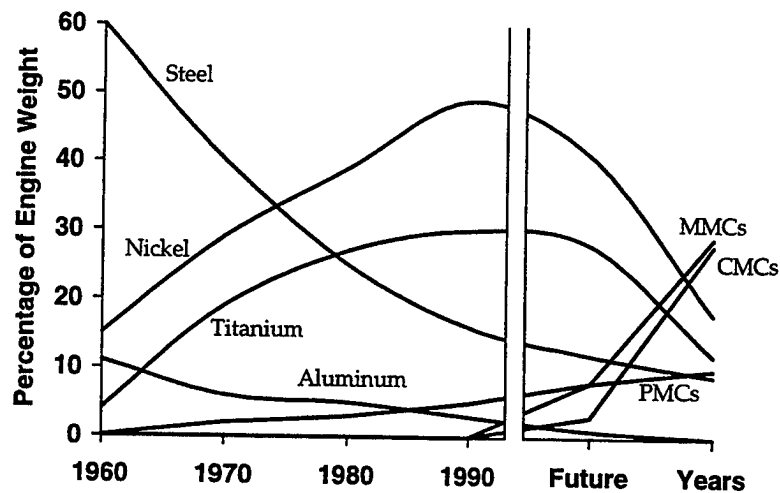
The identification of potential concerns of assured, affordable access and the determination of possible policy options to deal with them in the advanced materials sector are complicated by: (1) new approaches to defense acquisition; (2) issues concerning the transition of one advanced material to another; and (3) the number of tradeoffs to be considered in funding the transition to a new material. This chapter summarizes the assessments reported in Chapters 2 and 3 in terms of the capability of the technology and industrial base to meet known and potential DoD demand as well as opportunities to reduce costs to DoD. This chapter concludes with a table that indicates the current status of all of the technologies evaluated in this report and possible policy options.

The advanced materials examined in this report have specific characteristics that indicate areas where their use in military systems provides performance characteristics that give U.S. forces a technological edge. In some cases, the materials have been used for military applications over several decades. In other cases, the materials represent promising emerging technologies that offer the potential for significant enhancement of military capabilities in weapon systems in the future.

A typical transition from one material to another is illustrated in Figure 4.1 which portrays trends in material usage in gas turbine engines. In 1960, these engines were principally steel. However 20 years later, titanium and nickel accounted for nearly 70 percent of the composition of these engines. The increase in PMC usage had also begun at this time, although PMCs are never expected to represent more than ten percent of the engine materials. Today, the use of nickel and titanium are at their projected zeniths. The incorporation of both MMCs and CMCs is forecast to rise rapidly. Together, these advanced composites are projected to constitute about 60 percent of the material used in gas turbine engines, perhaps by 2020. Similar transition curves could be drawn for material usage in other applications -- new materials are incorporated in a product when their price and performance characteristics for that particular product make them the most "attractive" option.

The definition of "attractive" is a function of many factors. Materials are chosen for use in military systems because (1) their performance is well understood, consistent, and satisfies a military requirement, and (2) they are reliable and maintainable in a cost effective manner. As new materials are characterized and used in R&D and prototypes, designers become aware of their performance and logistical characteristics and begin incorporating them in designs for new systems, upgrades of existing systems, and retrofits of parts and components.

Figure 4.1 - Material Usage in Gas Turbine Engines



Source: Aviation Week

The transition between one material and another is not simply a function of satisfying absolute military requirements. Cost has become an independent variable in programmatic acquisition decisions, with cost goals established for each phase of a program. In this way, effectiveness is increased while remaining within the bounds of constrained resources. In fact, replacing currently used materials with more advanced materials involves numerous tradeoffs. These tradeoffs include cost, capability, availability of the material, environmental issues, reliability, and maintainability.

These tradeoffs reflect today's military environment which is characterized by fiscal constraint and reduced threat. This new environment has manifested itself in a new approach to defense acquisition -- an approach that relies more on utilizing commercial development in lieu of paying higher prices for military unique products and processes.

The combination of this new approach to defense acquisition, issues concerning the transition from one advanced material to another, and the number of tradeoffs being considered has resulted in increased complexity in examining and potentially taking actions on issues of assured, affordable access. There are three broad categories of situations that may arise in conducting such examinations.

- (1) A funded program to satisfy a military requirement that meets a well-defined, unambiguous operational need: This situation can be treated quantitatively. The cost and technological risk of various alternatives can be compared. Cost and performance tradeoffs can be conducted. For example, the use of continuous fiber-reinforced ceramics is an important contender to reduce the infra-red signature of military engines and consequently lowers vulnerability to heat-seeking missiles. This crew survivability application could satisfy an

unambiguous DoD requirement that must be funded, independent of the maturity of the commercial applications of the enabling technology. However, investments that improve the affordability of the technology should also be considered.

- (2) A statement of desirable military performance that DoD systems will eventually have but absent a specific program funding its incorporation: This situation, by itself, is not sufficient to justify taking action on issues of assured or affordable access. It is, however, appropriate to conduct the R&D to develop the capability and to demonstrate its effectiveness.
- (3) An opportunity to reduce costs to DoD: Because of the nature of the advanced materials examined in this report, their desired performance characteristics are often accompanied by reductions in the life cycle costs of systems or components. Therefore cost and benefit analyses may be used to justify retrofit or upgrade programs on their own merits. In addition, such programs may be the catalyst for initiating other defense or commercial applications which ultimately reduce production costs to the extent that DoD is able to fund desirable military performance programs.

The following pages summarize this assessment's findings on issues of assured and affordable access for specialty metals and advanced composites in this context.

Specialty Metals

The analyses of specialty metals are more straightforward than those for advanced composites. Specialty metals have been used for a long time and DoD applications are widespread. In many cases, specialty metals are planned for replacement by a more advanced material with even better properties. If an opportunity to insert a specialty metal in a military system were to arise, the industrial base to manufacture the new item would be available. In general the situation for specialty metals is characterized as follows:

- The industrial base is mature.
- The materials have been used by DoD and commercial companies for many years.
- Defense spending represents a major portion of the industry's business base.
- Corresponding to declining defense requirements, the industry is facing significant reductions in defense spending.
- There could be additional market pressures from low price competition from the former Soviet Union (beryllium).

- The industrial base is restructuring because of significant overcapacity generated from these DoD cutbacks and FSU sales.
- To varying extents, increased commercial applications offset some of the military sales declines (to a large extent for beryllium products except metallic beryllium, some impact for titanium, and little impact for superalloys).
- The long term (10 to 20 years) defense market outlook is weak because of the rising competition with advanced composites (assuming composite costs decrease significantly).

Concerning issues of assured, affordable access to specialty metals to satisfy defense needs, this study has, as of now, concluded the following:

- The industrial bases for these specialty metals will downsize to reduce overcapacity according to normal competitive market forces.
- This downsizing will not be inconsistent with future defense requirements, and therefore issues of assured or affordable access do not appear significant.
- If titanium prices could be reduced by 40 percent, some significant increases in defense demand could be expected. It is the responsibility of industry to address these cost reduction issues unless a specific cost benefit analysis shows that it is in the best interest of DoD to take action.

PMCs

PMCs are the most mature of the advanced composites examined in this assessment. In this regard, the situation is similar to specialty metals. There are numerous DoD applications. The industrial base is well situated to support insertion opportunities when they arise. However, the overall outlook for PMCs is much more favorable than specialty metals. Increased commercial PMC use in the future is expected. Broad findings are as follows:

- The industrial base is mature.
- The materials have been used by DoD and commercial companies for many years, in fact there is a very large commercial market for less advanced PMCs.
- Defense spending constitutes a major portion of some segments of the industry's business base (principally PMC fabricators).

- The industrial base is restructuring because of declines in defense spending (principally PMC fabricators), however the changes are not severe.
- Increased commercial applications in some cases have already and, in other cases, will soon offset the military sales declines.
- DoD demand will soon begin to grow, but not as rapidly as commercial demand.

Concerning issues of assured, affordable access to PMCs to satisfy defense needs, based on data examined to date, this study has concluded the following:

- There is little doubt that the PMC industrial base will be able to satisfy military needs in the future.
- There are certain areas (pitch-based carbon fibers, PMC fabrication) where the costs to DoD could be reduced, and projects are underway to attempt to achieve such cost reductions.
- Potential PMC insertion opportunities may arise, although this study has not identified any particular projects. Because insertion projects increase production, they can only improve DoD's access to PMCs. However, DoD funding for any insertion project must be contingent on that project passing a cost-benefit test on its own merits. A potential insertion project must show that the expected life cycle costs to DoD are reduced as a result of the project and that the inserted product performs at least as well as the item that it replaced.

CMCs

CMC technology is less mature than PMC technology. In general terms, the broad findings are as follows:

- The industrial base is healthy and growing rapidly for dCMCs; the industrial base is small but beginning to exhibit stability and growth potential for cCMCs.
- Structural dCMCs have been used by DoD and the commercial world for many years, and there is a very large industrial base for other ceramics applications. cCMCs are an emerging technology.
- While defense spending constitutes an important portion of the industry's business base, energy and environmental usage are far more important.

- Government spending has not declined significantly, only its growth has been slower than anticipated a few years ago.
- DoD demand will continue to grow.
- Commercial demand, especially for energy and environmental applications, is expected to grow more rapidly.

Concerning issues of assured, affordable access to CMCs to satisfy defense needs, this study has, at this time, concluded the following:

- There is little doubt that the CMC industrial base will be able to satisfy military needs in the future.
- DoE investments in CMCs will serve DoD needs in that those capabilities being developed will also satisfy military requirements. Therefore, it is not necessary for DoD to have the lead in technology development.
- As was the case with PMCs, potential CMC insertion opportunities may arise, although this study also has not identified any particular projects. DoD funding support for any insertion project should be contingent on a demonstration that the expected life cycle costs to DoD are reduced as a result of the project and that the inserted product performs at least as well as the item that it replaced.

MMCs

Applications for MMC technology are less mature than CMC technology. The principal difference in the situation is that potential DoD demand for MMCs is greater and therefore DoD has a clear interest and leadership role in seeing this technology move into application for improving both the performance and affordability of weapon systems. Broad findings are as follows:

- The market for dMMCs is small and not stable even though there is substantial installed capacity; the industrial base for cMMCs is precompetitive.
- Both dMMCs and cMMCs are emerging technologies.
- Potential dMMC DoD demand may be the highest of the advanced composites examined.
- While potential cMMC demand will not be large, it will be higher than cCMCs and lower than dCMCs.

- No high volume DoD application for cMMCs can be supported with the current industrial base.
- There is significant industrial capacity for particulate-reinforced dMMCs.

Concerning issues of assured, affordable access to MMCs to satisfy defense needs, this study has concluded the following:

- There are potential issues of assured, affordable access -- industry is not capable of satisfying a high volume DoD demand for cMMCs.
- Low volume cMMC production costs are high.
- Use of cMMCs provides a near-term opportunity to reduce total DoD life cycle costs and to improve the military capability of gas turbine engines. However, the current precompetitive industrial base cannot produce the cMMCs in sufficient volume.
- The numerous technical and economic barriers to widespread use identified in this assessment cannot be overcome by industry alone. Although industry and government together have made progress, there has been little application specific investment to ensure an item is producible.
- The identified technical and economic problems are not insurmountable. A project, identified in this report, would contribute considerably to resolving these issues by establishing long term, viable producers capable of meeting potential DoD quantity cMMC demands through the transition of manufacturing technology developed by industry from pilot scale to full scale production.
- DoD has not quantified high volume requirements for dMMCs. While access seems assured, the issue of affordability cannot be addressed until the demand is well established.

High Thermal Conductivity Composites

High thermal conductivity composites are the least mature of the advanced materials examined in this report. They also have the lowest potential DoD demand. The general findings are as follows:

- The industrial base is precompetitive.

- DoD demand is small and for very high end technology.
- The cost of the material is very high.
- DoD demand can be met with the current industrial base structure.
- DoD demand will remain small unless commercial industry develops large scale applications that will significantly lower the price.

Concerning issues of assured, affordable access, this study has, based on the data examined to date, concluded the following:

- There are no issues of assured access, and DoD is funding its unique requirements.
- DoD costs will probably not decline substantially because of low volume production.
- Lower DoD costs and increased DoD usage will only occur when volume commercial production applications materialize. Based on current needs and costs, it would be incumbent on industry, not DoD, to develop such commercial applications and markets.
- At this time, there are no obvious needs for an insertion project. Should one materialize, funding support must be justified by a cost-benefit analysis.

Conclusion

Table 4.1 portrays the above discussion in chart form. It summarizes potential issues of assured, affordable access and identifies some possible policy directions. The rows of the table represent the technologies and characteristics of the industrial bases for each of the advanced materials examined in this report. The technologies are classified according to the following scheme: defense unique; access assured and commercial capabilities sufficient; access is assured but affordability may be an issue; access is assured but development of leading edge technology may be an issue; and access to the technology is not assured. Possible actions include: (1) investment in R&D on dual use technologies to ensure our commercial technology base remains at the leading edge in areas critical to the U.S. military; (2) integration of military technologies into commercial production through (a) transition into commercial applications or (b) developing and deploying new manufacturing technologies for more affordable capabilities; and (3) insertion of commercial capabilities into military systems.

Table 4.1 - State of Advanced Materials Technology and Possible Policy Actions

Technology / Product Area Needed for Military Requirements		Commercial Capabilities Can Meet Some Military Requirements				Possible Policy Options			
		Access is Assured & Commercial Capabilities Alone Will Be Sufficient	Access is Assured But DoD Needs Affordability in High End Technologies	Access is Assured But DoD Needs to Ensure Commercial Suppliers Can Supply Leading Edge Technology	DoD Needs Assured Access to Technology and Industrial Capabilities	R&D Investment	Develop and Deploy New Manufacturing Technologies	Transition Defense Technology to Commercial Applications	Insert Commercial Technology
Specialty Metals	Superalloys	X							
	Titanium	X	? ¹				Y		
	Beryllium	X							
PMCs	Matrix Resins	X							
	PAN fibers	X							
	Pitch fibers		X				X		
	Other Reinforcement Fibers	X							
	Prepreg Suppliers	X							
	Fabricators		X				X	X	Y
CMCs	Ceramic powders	X							
	Reinforcement Producers	X							
	dCMC Fabricators	X							Y
	Continuous Fibers		X	X		X	X		
	cCMC Fabricators	X							Y
MMCs	dMMC fabricators	X	? ³				X		Y
	cMMC fabricators				X		X		Y
	Whiskers				? ²		X		
	Continuous Fiber suppliers				X	X	X		
High Conductivity Materials	Fabricators					X	X	X	

X implies applicability of the technology classification or possible policy option.

Y implies that an option is possible if the benefits outweigh costs.

¹ If titanium prices could be reduced by 40 percent, some significant increases in defense demand could be expected. It is the responsibility of industry to address these cost reduction issues unless a cost benefit analysis shows that it is in the best interest of DoD to take action.

² No established requirement.

³ Affordability cannot be addressed at this time.

Overall, Table 4-1 implies that, with few exceptions, assuming the programs ongoing in DoD and other government agencies continue as planned, the technology and industrial base for advanced materials is as of now adequate for meeting future military requirements.